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Institute of Polar Studies

Report No. 34

# STRATIGRAPHY AND PETROLOGY OF THE MAINLY FLUVIATILE PERMIAN AND TRIASSIC BEACON ROCKS, BEARDMORE GLACIER AREA, ANTARCTICA

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# ERRATA

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"Stratigraphy and Petrology of the Mainly Fluviatile Permian and Triassic Beacon Rocks, Beardmore Glacier Area, Antarctica"

In modal analyses of samples from the Buckley, Fremouw, and Falla Formations (Tables 9, 13, and 15, respectively), the percentage in the "REST" category should be reduced by the percentage in the "PR/ZEOL" category. Analyses for samples with more than 20 percent calcite, prehnite, or zeolite are correct as they stand.

ABSTRACT

The near horizontal Beacon strata (Devonian?-Triassic) of the Beardmore Glacier area rest on a peneplain cut mainly in a Precambrian to Lower Paleozoic graywacke and phyllite sequence intruded by granitic plutons. The 2600-m-thick Beacon sequence comprises eight formations; the Alexandra Formation (Devonian?), the Pagoda, Mackellar, Fairchild and Buckley Formations (Permian), the Fremouw and Falla Formations (Triassic), and the Triassic?-Jurassic Prebble Formation. The Ferrar Group (Jurassic), which overlies and intrudes the Beacon rocks, comprises the Kirkpatrick Basalt and Ferrar Dolerite. This study is concerned mainly with the stratigraphy and petrology of the Permian and Triassic Beacon strata above the glacial Pagoda Formation.

The Mackellar Formation, which conformably overlies the Pagoda Formation, consists of 60 to 140 m of laminated medium- to dark-gray shale and light-gray fine-grained sandstone, but the proportion of sandstone increases to the northwest. Current flow was southeasterly. The formation was deposited in a quiet body of water extending for 1000 km along the Transantarctic Mountains from the Queen Elizabeth Range to the Ohio Range; $Sr^{87}/Sr^{86}$ ratios suggest a nonmarine environment.

The Fairchild Formation consists of 130 to 220 m of arkosic sandstone deposited by southeast-flowing streams. The sand was derived from a granitic and metasedimentary source, though some may have been reworked glacial debris.

The Buckley Formation is a crudely cyclic coal-bearing sequence about 750 m thick; sandstone beds rest on erosion surfaces and grade upward into carbonaceous shale. Coal forms as much as six percent of the section. Leaves (mainly Glossopteris) and stems are common. Buckley sandstone had two nonvolcanic sources; quartz - plagioclase - K-feldspar sand from the west, and quartz-plagioclase sand from the north. Intermediate-acid volcanic detritus appears 100-300 m above the base of the formation and dominates the sandstones in the upper part.

The Triassic Fremouw Formation consists of three parts: the lowest is a 100-m-thick cyclic sequence of quartzose sandstone and greenish-gray siltstone; the middle, 200 m thick, is mainly siltstone and includes sandstone with volcanic fragments; the upper 300 m is mainly similar volcanic sandstone, although the beds become carbonaceous toward the top. A labyrinthodont jawbone fragment was discovered near the base of the formation, and leaves of Dicroidium and logs were found near the top; root impressions occur throughout.

The Falla Formation, which is from 160 to 530 m thick, is a cyclic sandstone-shale sequence in the lower part. The sandstone is more

quartzose than that below, but it is diluted progressively up the section by volcanic material. The upper part of the formation is dominated by vitric tuff. Accretionary lapilli suggest at least one volcanic center within the Queen Alexandra Range. The Fremouw and Falla Formations were deposited on a flood plain with streams flowing to the northwest, in contrast to the southeast-flowing Permian streams.

The Prebble Formation, from 0 to at least 460 m thick includes laharic deposits, agglomerate and tuff, and is overlain by Kirkpatrick Basalt. Several diabase sills, normally from 50 to 200 m thick, intrude the strata between the Pagoda and Falla Formations.

Metamorphism by the sills has resulted, in the Buckley and Fremouw Formations, in locally extensive laumontite replacement of plagioclase, volcanic grains and matrix in the volcanic sandstones. Replacement minerals in the Falla and Prebble Formations include clinoptilolite, analcime and mordenite. A few sandstones in the Buckley and Fremouw Formations contain prehnite and grossularite.

ACKNOWLEDGMENTS

The writer thanks R. J. Baillie, Dr. D. H. Elliot, D. Johnston, and Dr. J. F. Lindsay for their good company, and willing assistance in the field. The field work was carried out between November 16, 1966, and February 7, 1967, and between November 11, 1967, and February 2, 1968. Stratigraphic sections at Mount Miller and Mount Weeks (CO) were measured jointly with Dr. Lindsay. The support and cooperation of the Office of Antarctic Programs at the National Science Foundation, the U. S. Navy Task Force 43, and particularly the crews of the LC-130 Hercules aircraft of Air Development Squadron Six are gratefully acknowledged. Financial support for the project was provided through National Science Foundation grants GA-534, GA-1159 and GA-1617 to The Ohio State University Research Foundation.

This report is based on a Ph.D. dissertation (Barrett, 1968) supervised by Dr. Charles H. Summerson, and critically reviewed by Drs. D. H. Elliot, G. W. Moore, Jr., J. M. Schopf and C. H. Summerson. Discussions with the above, and with Dr. V. H. Minshew, now at the University of Mississippi, on various aspects of Beardmore geology are much appreciated.

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# INTRODUCTION

The Transantarctic Mountains in the Beardmore Glacier area (Figs. 1, 2) are bounded on the northeast by the Ross Ice Shelf, from which rugged ice-clad foothills extend about 30 km inland and rise to about 2000 m. Beyond the foothills the main ranges of the Transantarctic Mountains form snow-covered flat-topped massifs with an average elevation of about 3000 m, which disappear gradually southwestward beneath the ice of the South Polar Plateau.

This two-fold topographic division of the central Transantarctic Mountains reflects a major geological boundary. The foothills consist almost entirely of a thick sequence of Late Precambrian or Early Cambrian graywacke and phyllite intruded by Early Paleozoic granitic plutons. On this basement complex there is an extensive erosion surface of low relief, which is overlain by a near horizontal Devonian? to Triassic nonmarine clastic sequence--the Beacon rocks.

The purpose of this study is to describe and interpret the mainly fluviatile Permian and Triassic Beacon rocks, which extend from the top of the glacial beds through a thickness of about 2000 m to the base of the tholeiitic flows of the Ferrar Group. An analysis of the Beacon paleocurrent data will be published elsewhere (Barrett, in preparation, a), but the data are summarized in Fig. 3.

Color geologic maps of the Beardmore Glacier area at a scale of 1:250,000, showing the distribution of individual formations in the basement and Beacon rocks, and that of the larger diabase sills, are being prepared at the Institute of Polar Studies. The first sheet, the Mount Rabot Quadrangle (Barrett, Lindsay and Gunner, in press) is expected to be published by June, 1970.

# PREVIOUS WORK

Rocks of the Beardmore Glacier area were first viewed and described by Ernest Shackleton and his party during the 1907-09 British Antarctic Expedition. According to Shackleton (1909), a gently-dipping sedimentary sequence at least 450 m thick dominated by massive sandstone in the lower part and with coal seams in the upper part was found at Buckley Island, near the head of the Beardmore Glacier. The similarity between these beds and the Beacon Sandstone Formation of south Victoria Land (Ferrar, 1907) was immediately recognized. Three years later Scott's ill-fated party, on their return journey from the South Pole in 1912, discovered *Glossopteris* leaf impressions at Buckley Island, establishing for the first time the presence in Antarctica of Permo-Triassic strata similar in age, as well as in lithology, to those of the other Gondwana continents.

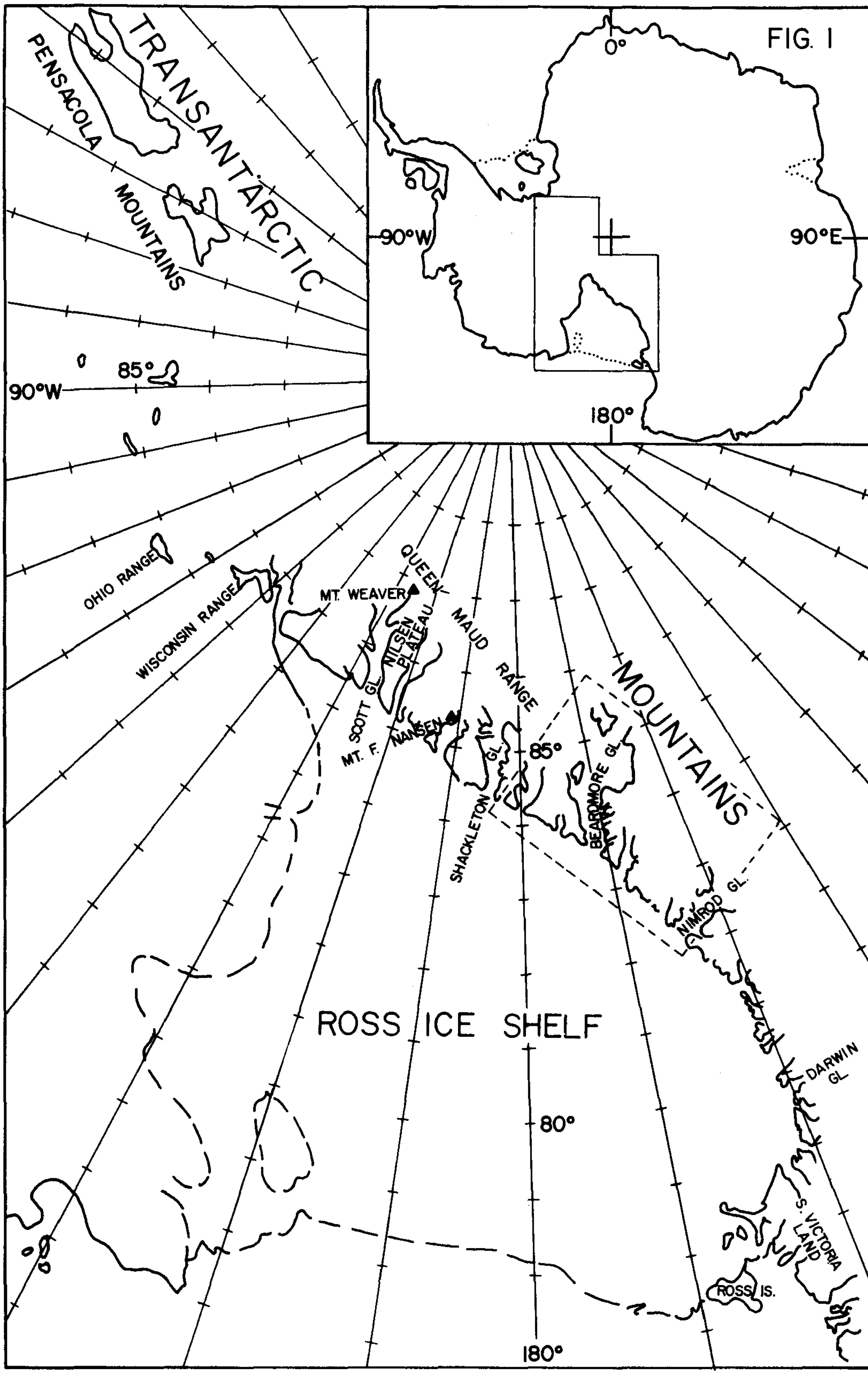



Figure 1. The central Transantarctic Mountains. The dashed line encloses the Beardmore Glacier area.

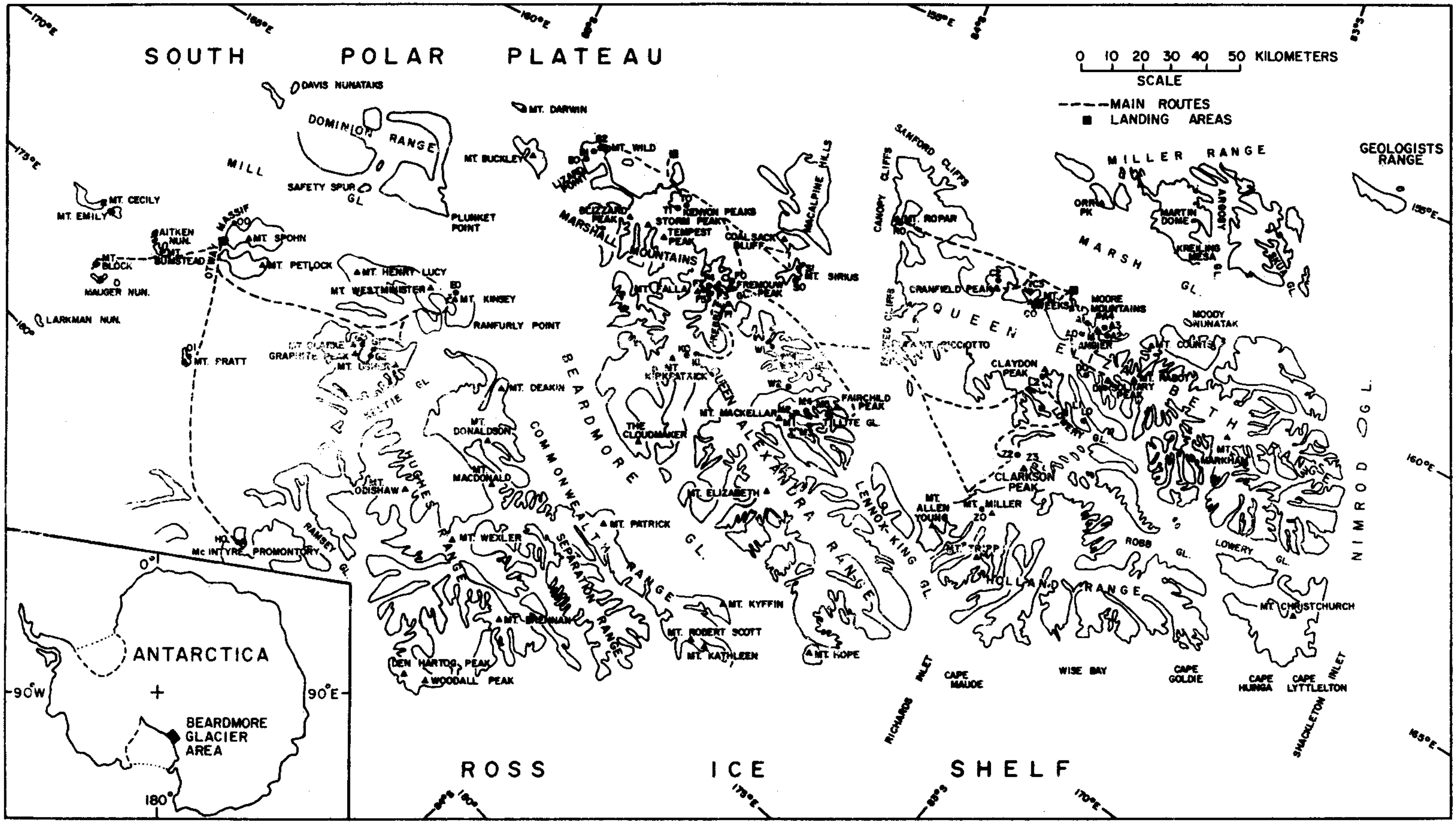



Figure 2. Beardmore Glacier area, central Transantarctic Mountains, showing the location of stratigraphic sections.

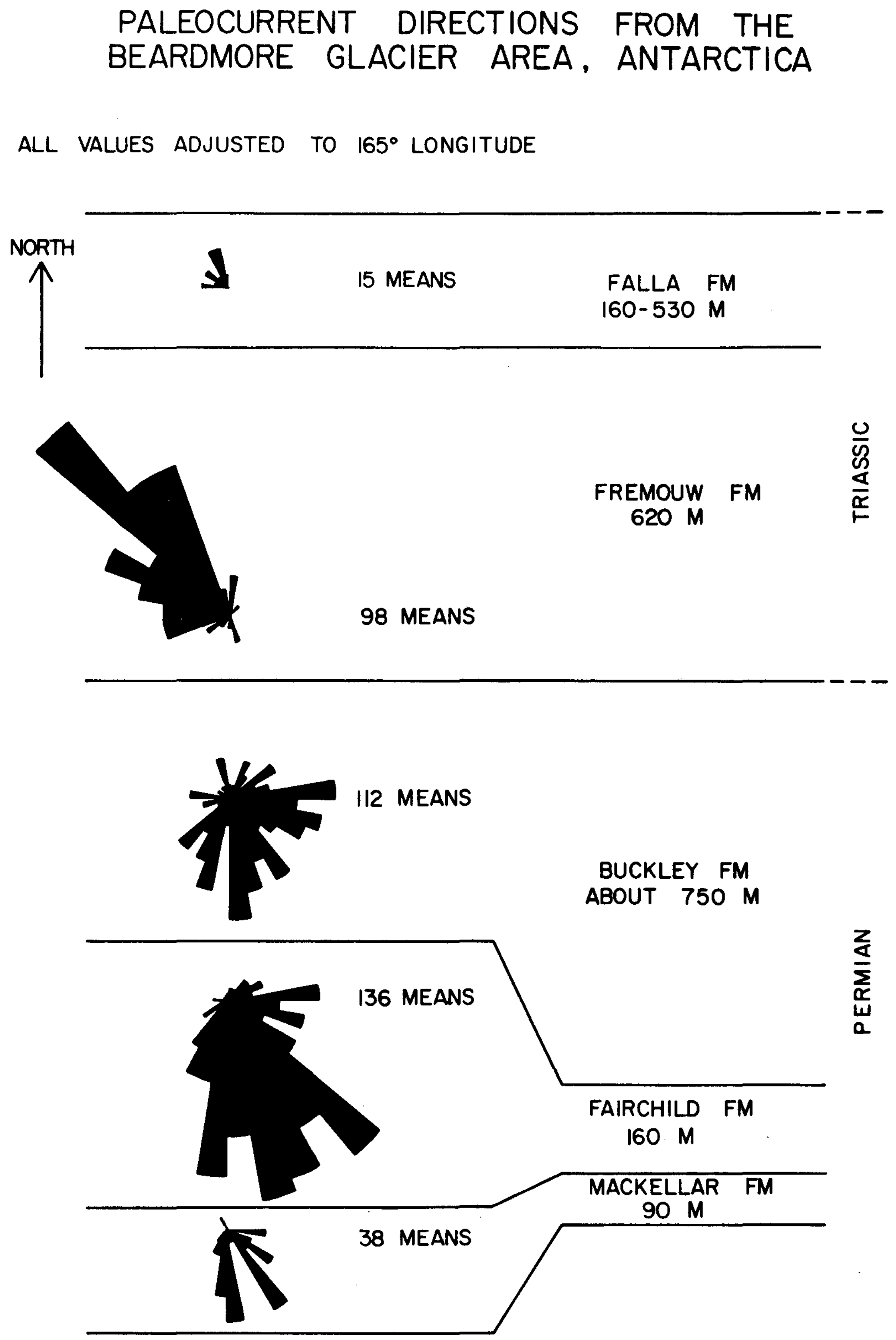



Figure 3. Summary of paleocurrent directions measured from small- and medium-scale crossbedding and parting lineation in the Permian and Triassic rocks of the Beardmore Glacier area. Each direction is the mean of several readings from a small (less than 10 m thick) stratigraphic interval.

The area was not visited again for almost half a century, until the International Geophysical Year stimulated a new interest in the Antarctic. In 1957, J. H. Miller and G. Marsh, members of the New Zealand section of the British Commonwealth Transantarctic Expedition, found *Glossopteris*-bearing coal measures at Cranfield Peak in the Queen Elizabeth Range. Two years later another New Zealand expedition discovered similar coal measures containing *Glossopteris*, in the upper part of a nearly horizontal sequence an estimated 1500 m thick, in the Holland Range 80 km to the north (Gunn and Walcott, 1962).

A new phase in the geological exploration of the area began with the work of two four-man parties of the New Zealand Geological and Survey Expedition in the summer of 1961-62. McGregor (1965) of the southern party examined and reported on the Beacon rocks on the southeast side of the Beardmore Glacier, where he found, in ascending order: *Glossopteris*-bearing coal measures, an unfossiliferous cyclic sequence, Triassic coal measures and tholeiitic basalt flows. Grindley, geologist with the northern party, examined and described most of the Beacon strata on the northwest side of the Beardmore Glacier, where in one place or another every part of the 2600-m-thick section from the basement complex to the basalts can be found. For the first time a formal stratigraphy for the area was proposed (Grindley, 1963).

In the 1965-66 season a New Zealand party spent one month on Buckley Island (Young and Ryburn, 1968), where they found strata equivalent to Devonian(?) and Permian units defined by Grindley (1963).

## STRATIGRAPHY AND PETROGRAPHY

### Introductory Remarks

The stratigraphy is discussed in three parts which correspond approximately to the three periods of time (Permian, Triassic, and Jurassic) represented by the postglacial strata in the Beardmore area. The Permian and Triassic Beacon strata are of primary interest in this study, but a short discussion of the Jurassic Ferrar Group has been included also.

The term Beacon is used here informally, but in the same sense in which it has been used by Antarctic geologists since it was proposed by Ferrar (1907), the only known exception being Hamilton and Hayes (1963). The Beacon encompasses the strata of East Antarctica that overlie with nonconformity or angular unconformity the Lower Paleozoic and Precambrian basement complex, and range in age from Devonian to Triassic or possibly Early Jurassic. Excepted from the Beacon are rocks of the Ferrar Group, the tholeiitic rocks of Jurassic age that intrude and overlie the Beacon strata.

Table 1 compares the stratigraphy of the Beardmore Glacier area with the stratigraphy in other parts of the central Transantarctic mountains. Lithologic equivalents within the Beardmore Glacier area are shown in Fig. 4 (stratigraphic sections, in back). The sections and the localities at which they were measured (Figs. 2 and 4), are referred to in diagrams and in the text by a letter designating the area and a number indicating the locality in the area; that is, F2 is section 2 in the Mount Falla area. For sample identification, the first two characters identify and locate the stratigraphic section and the second two give the number of the sample in the section. For example, GO32 refers to sample 32 in section GO.

## Stratigraphic Summary

In the Beardmore Glacier area the basal Beacon beds, quartz arenite of the Alexandra Formation (Grindley, 1963), lie with angular unconformity on an erosion surface cut in a thick sequence of low rank metasedimentary rocks intruded by granitic rocks. The Alexandra Formation is disconformably overlain by the Permian Pagoda Formation, a unit predominantly glacial in origin (Lindsay, 1968a).

The oldest unit described here in detail, the Permian Mackellar Formation, overlies the Pagoda Formation with apparent conformity and consists mainly of dark shale and fine-grained sandstone. The Mackellar Formation is succeeded by a massive arkosic sandstone unit, formerly the lower part of Grindley's Buckley Coal Measures (Table 2), but here named the Fairchild Formation. The contact with the overlying Buckley Formation (the Permian coal measures proper) is marked, over most of the area, by a zone containing well-rounded white quartz pebbles. Where such pebbles were not found, beds of coarse grit occupy this stratigraphic position. The Buckley Formation is a crudely cyclic sequence of sandstone, shale and minor coal. The sandstone is mainly arkosic in the lower 100 m, but many of the higher sandstone units are dominated by volcanic detritus. The Buckley Formation also contains leaf impressions (mainly of *Glossopteris*), logs, and a few roots.

The Buckley Formation is disconformably overlain by the Triassic Fremouw Formation (new formation), which consists mostly of alternating sandstone and mudstone. The latter is characteristically greenish gray in the lower and middle parts of the formation, in contrast to the medium- and dark-gray shale of the underlying Buckley Formation. Sandstone in the Fremouw Formation is quartzose in the lower 100 m, but contains considerable amounts of feldspar and volcanic detritus throughout the rest of the formation. A jawbone fragment of a labyrinthodont amphibian (Barrett and others, 1968a) was recovered from a quartzose sandstone bed in the lower part of the Fremouw Formation. The upper part of the Fremouw Formation contains beds with root impressions, stem impressions, and in the uppermost 100 m logs and coal seams as well. The overlying Falla Formation (the upper part of the Falla Formation of Grindley, 1963) is, in the lower part, a cyclic sequence of sandstone

Table 1. Comparison of the postglacial Beacon stratigraphy in the Beardmore Glacier area with that of other areas in the central Transantarctic Mountains.

| | OHIO RANGE<br>Long 1965 | WISCONSIN RANGE<br>Minshew 1966 | MT. WEAVER<br>Doumani and Minshew 1965 | NILSEN PLATEAU<br>Long (in prep) | MT. FRIDTJOF NANSEN<br>Barrett 1965 | SHACKLETON GLACIER<br>Wade and others 1965 | SUPPORTERS RANGE<br>McGregor 1965 | This paper | NIMROD GLACIER<br>Laird and others (in prep) | DARWIN GLACIER<br>Haskell and others 1965 |
|---|---|---|---|---|---|---|---|---|---|---|
| JURASSIC | | | | | | Kirkpatrick Basalt | Kirkpatrick Basalt | Kirkpatrick Basalt | | |
| TRIASSIC | | | | | | Dominion Coal Measures | Dominion Coal Measures 400 + m | Prebble Fm. 0 m to 460 + m<br>Falla Fm. 160-530 m | | |
| | | | | Nilsen Fm. 180 m | | Falla Fm. 565 + m | Falla Fm. 400 + m | Fremouw Fm. about 650 m | | Ellis Fm. 30 + m |
| PERMIAN | Mt. Glossopteris Fm. 750 + m | Queen Maud Fm. 25 + m | Queen Maud Fm. 600 + m | Queen Maud Fm. 110 m to 210 m | Unit C 280 + m | Buckley Coal Measures 473 m | Buckley Coal Measures 330 + m | Buckley Fm. Measures about 750 m | | Misthound Coal Measures 93 m |
| | | Weaver Formation: upper member 130 m | Weaver Formation: upper member 70 m | Amundsen Fm 205 m | Unit B 210 m | Mackellar Formation: upper member 167 m | | Fairchild Fm 130 - 220 m | Buckley Coal Measures 350 + m | erosion |
| | Discovery Ridge Fm. 180 m | middle member 220 m | middle member 70 m | Roaring Fm. 52 m | Unit A 125 m | lower member 137 m | | Mackellar Fm. 60 - 140 m | Mackellar Fm. 12 m to 110 m | interval |
| | | lower member 80 m | lower member 10 m | | | | | | | |

Scott Glacier Formation (glacial) and equivalents — Pagoda Formation (glacial) and equivalents

Table 2. A comparison of the stratigraphy of Grindley (1963), for the Queen Alexandra Range, and that proposed in this paper.

| Grindley (1963) | | This Paper | | |
|---|---|---|---|---|
| Kirkpatrick Basalts | | Kirkpatrick Basalt | Ferrar Group | JURASSIC |
| Ferrar Dolerites | | Ferrar Dolerite | | |
| not recognized | | Prebble Formation | Beacon strata | |
| Falla Formation | upper part | Falla Formation | | TRIASSIC |
| | lower part | Fremouw Formation | | |
| not recognized | | | | |
| Buckley Coal Measures | upper part | Buckley Formation | | PERMIAN |
| | lower part | Fairchild Formation | | |
| Mackellar Formation | | Mackellar Formation | | |

and dark shale with sandstone beds typically more quartzose than those in the upper part of the Fremouw Formation. The upper part of the Falla Formation consists mainly of beds of acid tuff. Elements of the Dicroidium flora, indicating a Triassic age, were recovered from both formations. The youngest Beacon rocks are assigned to the Prebble Formation (new formation), a unit that consists of volcanic conglomerate, agglomerate, tuffaceous sandstone and tuff.

The Jurassic Ferrar Group includes the tholeiitic Kirkpatrick Basalt and the Ferrar Dolerite, the latter being the intrusive equivalent of the basalt. The petrology and chemistry of the Ferrar Group are presently being studied by Dr. D. H. Elliot, Institute of Polar Studies, The Ohio State University.

## Petrographic Methods

### Modal Analyses

About 350 thin sections were examined and from these 178 were selected for modal analysis. The determinations were made using a Swift automatic point counter; the interval between points on each traverse was 0.3 mm, and between each traverse was 2 mm in most cases. For each thin section 400 to 600 points were counted, giving an accuracy of about 4 percent at the 95 percent confidence level for minerals with abundances between 20 and 40 percent, assuming correct identification (Van der Plas and Tobi, 1965). Table 3 gives the criteria that were used most commonly in identifying minerals and rock fragment lithologies during the counting.

The sandstone classification used to describe the mineral composition of these sandstones follows that of Folk (1968). The informal term "volcanic sandstone" is used where the rock contains more than 10 percent volcanic fragments, and includes all but the most quartzose volcanic arkose, the most quartzose feldspathic volcanic arenite, and the most quartzose volcanic arenite. The maximum quartz content for subarkose has been extended from 25 to 30 percent so that most nonvolcanic sandstone falls into the arkose or subarkose fields.

The identity of some original grains and matrix could not be determined because of the secondary formation of zeolite, prehnite, and some calcite. For consistency, calcite, zeolite and prehnite were counted as such, even though in a few instances the form or situation of the secondary mineral indicated the identity of the original material. Therefore, samples containing much secondary calcite or zeolite may have had a lower quartz content than their location on the quartz - feldspar - rock fragments ternary diagrams (see later) suggest. Some tuffaceous sandstones also may have had a slightly lower quartz content because many volcanic fragments are difficult to distinguish from the matrix, and some may have been counted with the matrix. Where mineral abundances have been summarized and quoted in the text, "$\overline{X}$" represents the arithmetic mean and "s" the standard deviation. Samples containing more than 20 percent calcite, prehnite or zeolite have been excluded from calculations of means for mineral composition and from ternary diagrams.

Table 3. Critieria most often used in identifying minerals and rock fragment lithologies during point counting.

| | |
|---|---|
| Quartz: | Low birefringence, no cleavage, clear or with sparsely-distributed specks, dust trails, vacuoles or needles. |
| K-feldspar: | Stained yellowish-green with sodium cobaltinitrite, extinction regular and complete. Some have polysynthetic twinning. |
| Plagioclase: | Low birefringence, good cleavage, usually cloudy from fine dark specks or from sericite flakes. Some have lamellar twinning. The nonvolcanic sandstones contain low temperature albite and oligoclase-andesine, and the volcanic sandstones contain low temperature and intermediate albite and oligoclase-andesine, but the plagioclase in the Triassic tuffs is normally high temperature basic oligoclase (determined by U-stage). |
| Intermediate-acid volcanic fragments: | |
| | a. Felsitic, light to dark brown, semiopaque, with some small (less than 10 microns) crystals with low birefringence. |
| | b. Felsitic, low-birefringent, fine-grained (Fig. 5). Some fragments have a wavy foliation with the appearance of relict vitroclastic texture; others contain indistinct circular structures, perhaps once vesicles. |
| | c. Felsitic, fine-grained, but stained yellowish-green by sodium cobaltinitrite. |
| | d. Crystalline randomly oriented feldspar laths (felted texture) from 20 to 100 microns long (Fig. 6). Groundmass is light to dark brown and semi-opaque where present. |
| | e. Crystalline, similar to d. but with subparallel laths (pilotaxitic texture). |
| | The fragments described in b. above are believed to be of pyroclastic origin; the others may be either of pyroclastic or of flow origin. |
| Other rock fragments: | A variety of quartz-feldspar-mica aggregates and foliated micaceous fragments. The former |

represent arenaceous sedimentary and metasedimentary rocks; the latter represent the pelitic rocks.

| | |
|---|---|
| Muscovite: | Colorless, generally elongate, with excellent often sinuous cleavage and high birefringence. |
| Biotite: | Colorless to dark-brown or reddish-brown, normally pleochroic, with excellent, often sinuous, cleavage and moderate birefringence. |
| Chlorite: | Colorless to pale green, excellent cleavage, very low birefringence. |
| Calcite: | Extreme birefringence and variable but high relief. |
| Prehnite: | Colorless, moderate positive relief, moderate birefringence, length fast. Some aggregates have spherulitic extinction. |
| Analcime: | Colorless or pale pink, moderate negative relief, isotropic. |
| Grossularite: | Colorless, high positive relief, isotropic, normally in the form of scattered small equant crystals. |
| Zeolite: | Colorless, low to moderate negative relief, birefringence higher than feldspar or even quartz in some cases, extinction is commonly undulose and twinning is rare. Occurs both as a cement and replacing feldspar or rock fragments. Incipient alteration of feldspar or rock fragments to zeolite is common in the Buckley, Fremouw, and Falla Formations. |

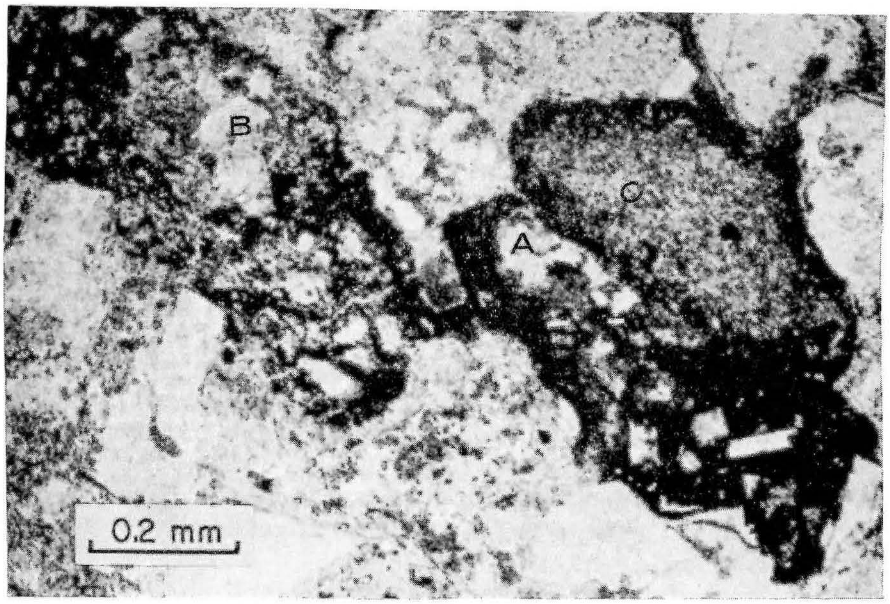



Figure 5. Altered volcanic fragments in a sandstone (L214) from the upper part of the Buckley Formation, Lowery Glacier. A - Feldspar laths in an opaque groundmass; B - Fragment with structures that may have been vesicular; C - Felsitic fragment. Plain light. Photo - J. M. Schopf

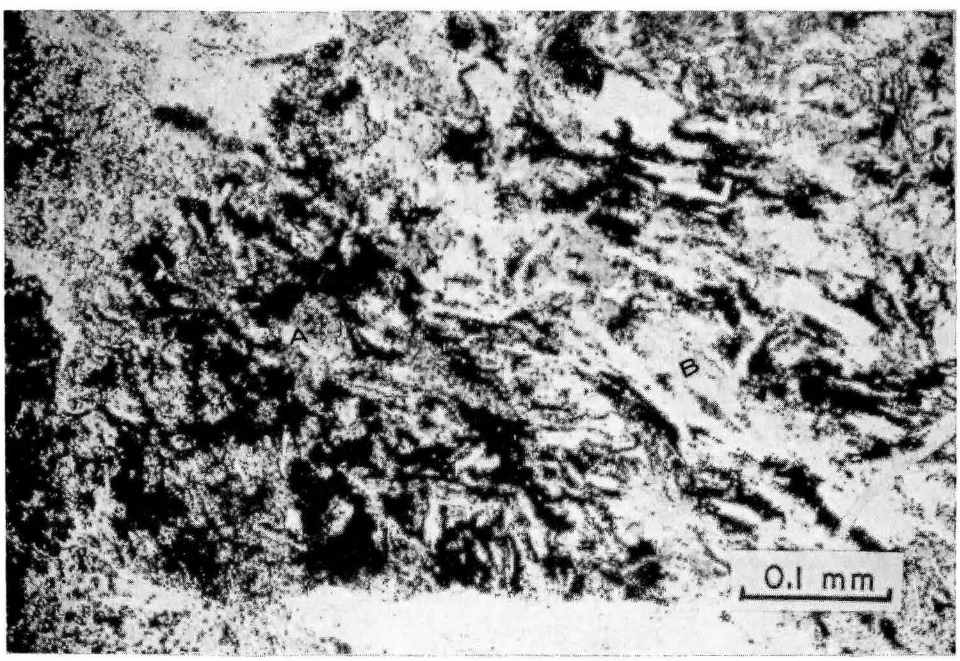



Figure 6. Two altered volcanic fragments in the sandstone figured above. A - Felted texture with feldspar microlites in an opaque groundmass; B - Poorly developed trachytic texture. Plain light. Photo - J. M. Schopf

## Grain Size Analyses

Grain size analysis on mechanically broken-down samples was not attempted for this suite of rocks because of the degree of alteration and induration of many of the samples. Instead, the grain size distribution was obtained by measuring grain diameters in thin section and applying the transformation of Friedman (1962). This transformation gives a grain size distribution comparable with a sieve analysis.

The measures of central tendency and dispersion used in later discussion of the analyses are the moment mean and standard deviation. Only measurements of grains of similar density, that is, quartz, feldspar and rock fragments, were used in the values calculated for Table 4.

# Permian System

## Mackellar Formation

### Definition

The Mackellar Formation was named by Grindley (1963, p. 329) to include "dark carbonaceous shales with sandstone bands overlying the Pagoda Tillite in the Beardmore region." Lindsay (1968a, p. 55), after further work in the type area at the head of the Tillite Glacier, described in detail, as the type section, a section 9 km north of Mount Mackellar (83° 54.5' S; 166° 33' E). Here the lowest strata of the Mackellar Formation consist of thin beds of black shale and light-gray fine-grained sandstone (Fig. 7), which conformably overlie massive pebbly greenish-gray mudstone of the Pagoda Formation. Diabase has been intruded along the contact of the Mackellar Formation with the overlying light-colored massive sandstone.

### Distribution and thickness

The Mackellar Formation crops out in a belt that extends north from Buckley Island to Mount Miller and then west to the Moore Mountains. The least thickness measured (55 m) is near Clarkson Peak (23), and the formation thickens to the south and west, reaching 140 m at Buckley Island (Young and Ryburn, 1968) and 143 m in the Moore Mountains (the sum of 89 m above the dolerite sill at A3, and 54 m measured by J. F. Lindsay below that sill 5 km to the northwest).

The Mackellar Formation has also been described from the central Nimrod Glacier area, where it varies from 12 to 107 m in thickness (Laird and others, in preparation). Wade and others (1965), in the Shackleton Glacier area, have assigned both a unit of carbonaceous shale and thin-bedded sandstone 137 m thick, and the overlying massive fins- to coarse-grained sandstone 167 m thick, to the Mackellar Formation. Only the carbonaceous shale unit is considered equivalent to the Mackellar Formation.

Table 4. Moment mean and standard deviation in phi units of the size distribution of quartzo-feldspathic and lithic grains in samples from the Beardmore Glacier area

| Sample | Mean | Standard Deviation | Sample | Mean | Standard Deviation |
|---|---|---|---|---|---|
| Mackellar Formation | | | Lower Fremouw Formation | | |
| Z301 | 4.37 | 0.92 | W116 | 1.94 | 1.02 |
| Z303 | 3.15 | 0.84 | W117 | 1.07 | 0.81 |
| L005 | 4.46 | 0.91 | L218 | 2.17 | 0.80 |
| L009 | 3.35 | 0.82 | F009 | 2.04 | 0.63 |
| Fairchild Formation | | | Middle & Upper Fremouw Fm. | | |
| B003 | 2.71 | 0.73 | F014 | 2.99 | 0.66 |
| B006 | 3.04 | 0.71 | F022 | 1.77 | 0.63 |
| M105 | 2.60 | 0.67 | F029 | 2.25 | 0.65 |
| M107 | 2.10 | 0.72 | F030 | 0.56 | 0.68 |
| M109 | 2.82 | 0.89 | F045 | 1.95 | 0.61 |
| Z304 | 2.04 | 0.72 | F048 | 2.39 | 0.72 |
| L011 | 2.77 | 0.88 | F056 | 2.49 | 0.67 |
| L013 | 1.70 | 0.62 | F404 | 2.70 | 0.80 |
| L018 | 2.92 | 0.93 | F509 | 2.23 | 0.63 |
| | | | F533 | 2.35 | 0.62 |
| | | | F537 | 1.90 | 0.72 |
| Buckley Formation (arkosic) | | | K101 | 2.40 | 0.87 |
| Z035 | 2.38 | 0.70 | | | |
| M114 | 2.11 | 1.00 | | | |
| L112 | 1.44 | 0.85 | Falla Formation | | |
| | | | F063 | 1.93 | 1.00 |
| | | | F067 | 2.65 | 0.81 |
| Buckley Formation (volcanic) | | | F406 | 2.34 | 0.76 |
| B200 | 1.98 | 0.98 | F201 | 1.93 | 0.70 |
| Z038 | 2.28 | 0.78 | F213 | 2.27 | 0.75 |
| L214 | 2.00 | 0.85 | F216 | 2.60 | 0.73 |
| | | | F222 | 2.29 | 0.81 |
| | | | F237 | 2.23 | 0.87 |
| | | | K006 | 2.18 | 0.85 |
| | | | K008 | 1.32 | 1.20 |
| | | | K028 | 1.39 | 0.76 |

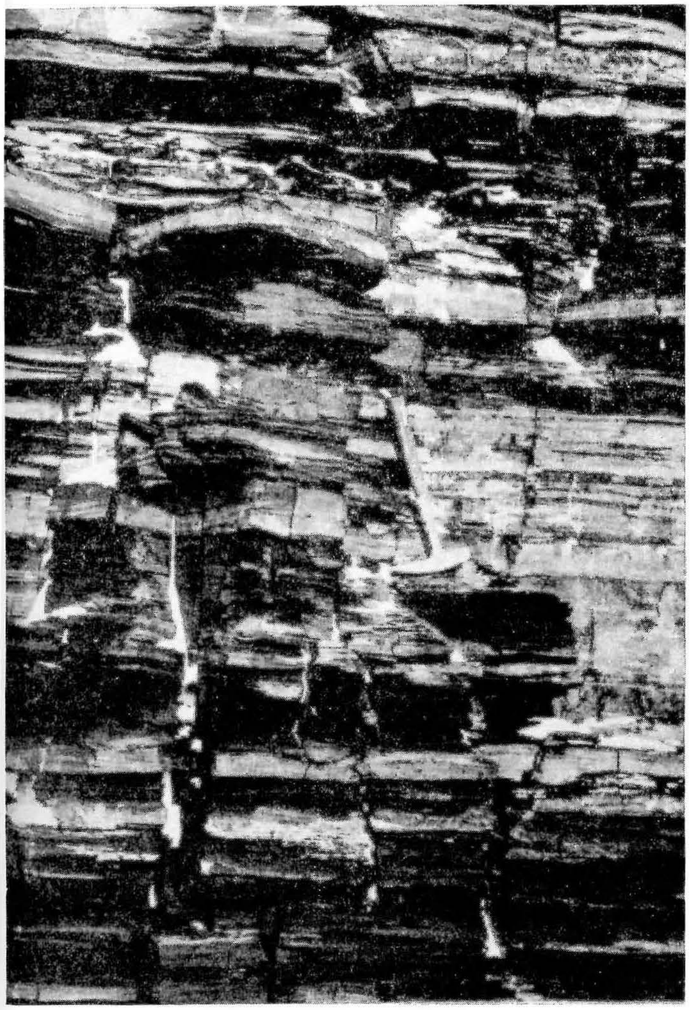


Figure 7. Laminated black shale from the Mackellar Formation at the type section near Mount Mackellar. Photo - J. F. Lindsay

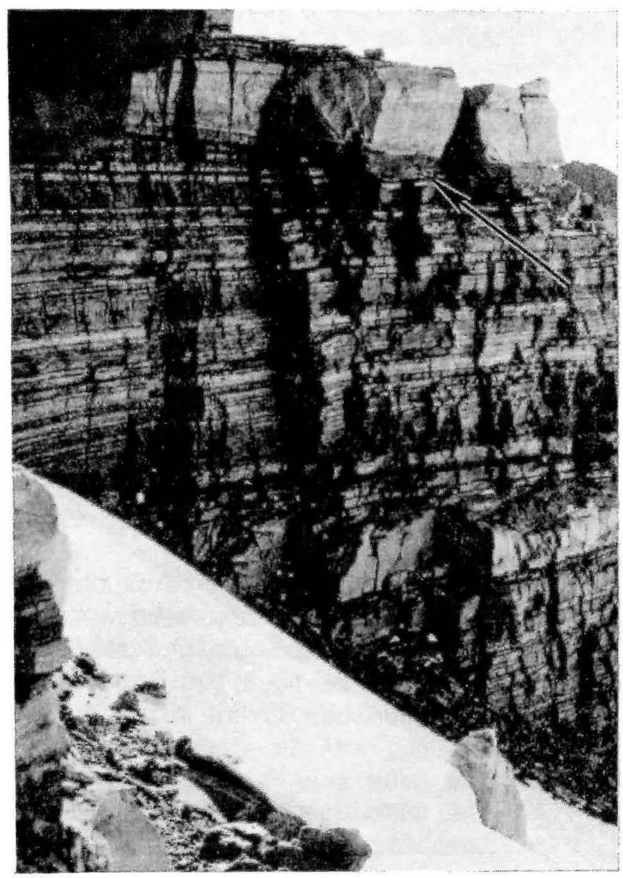


Figure 8. The middle part of the Mackellar Formation at A3, Moore Mountains, looking northwest. The channeled base of a "fining-upwards" cycle is arrowed.

### Lower contact

At the type section the lowest bed of the Mackellar Formation is a massive black fissile shale 2.8 m thick, which lies conformably on a massive medium- to coarse-grained sandstone typical of the Pagoda Formation (Lindsay, 1968a). At seven widely spaced localities (Fig. 2, M3, Z0, Z3, D0, D1, C0, A0) the lowest unit in the formation is a similar dark-gray to black shale from 4 m (M3) to 26 m (D0) thick. This unit overlies gray or greenish-gray pebbly shale or mudstone with, at some places, sharp, and at others gradational, contact. At the only other locality where the contact was examined (L0), no pebbles were found in the highest greenish-gray shale of the Pagoda Formation, and the basal black shale of the Mackellar Formation is only 2.4 m thick.

### Lithology

From the Tillite to the Lowery Glaciers the formation consists mainly of two lithologies; laminated medium-gray to black shale, which commonly is dominant, and light-gray to white very-fine-grained sandstone that in most cases is microcrosslaminated. Beds normally range from a few centimeters to about 1 m thick, though dark shale forms units as much as 26 m thick that contain only a few thin fine-grained sandstone beds. In some sections northwest of the Tillite Glacier, the formation includes sheets and lenticular units of massive fine to medium-grained sandstone from 5 to 25 m thick, which are more like the overlying Fairchild than the Mackellar Formation. In the western part of the area, the Queen Elizabeth Range, the Mackellar Formation is much sandier and dark shale is uncommon. Beds of fine- to medium-grained sandstone, like that of the overlying Fairchild Formation, alternate with similar or greater thicknesses of light- to medium-gray or greenish-gray very-fine-grained sandstone or siltstone. In the Moore Mountains, at A0, the contacts between these units are in most places gradational, but at A3 the sandstone and siltstone beds form at least two distinct "fining-upwards" cycles (Allen, 1965) 13 and 18 m thick. The coarser sandstone includes shale fragments near the erosional base of the cycle (Fig. 8), and grades upward into the finer sandstone or siltstone in which the overlying erosion surface is cut.

A number of white limestone beds as much as 30 cm thick and extending for many meters laterally are interbedded with dark shale and very- fine-grained sandstone in the Tillite Glacier area. Elsewhere, limestone beds are rare, although thin lenses of gray limestone that weather brown were found in the lower part of the formation at L0 and A0, and in the upper part of the formation at A3. The geometry of the beds suggests that they were deposited at about the same time as the adjacent clastic beds, but the limestones contain no structures to indicate under what conditions they accumulated. Spheroidal brown-weathering epigenetic calcareous concretions occur at several localities, particularly in the fine-grained beds.

Varvoid lamination was found within a few meters of the top of the Mackellar Formation in the Moore Mountains (A3) in an otherwise massive gray mudstone. There are two laminated intervals 10 cm thick, 1 m apart and 3 m below the top of the formation. Laminae counted on a 5-cm-thick sample (A309) average 4.5 mm in thickness and range from 2.8 to 7.0 mm. Each lamina is separated by a sharp contact and grades from a medium silt at the base to clay at the top.

Near the top of the Mackellar Formation at the head of the Tillite Glacier, there is a massive poorly-sorted green very-fine-grained sandstone about 25 m thick at M3 and 21 m thick at MO. At both localities the sandstone contains several spheroidal geodes about a meter across with crystals of calcite inside. A body of channel sandstone 3 m thick was found 8 m above the base of the massive sandstone at MO. The unit was not found in exposures of the formation other than at the Tillite Glacier, and Lindsay (1968a) noted its absence from the formation at the mouth of the glacier.

The only known exotic clasts in the Mackellar Formation, apart from those brought in by the Moore Mountains mudflow (Lindsay, 1968b). were found in a thin lens about 16 m below the top of the formation on the Tillite Glacier (MO). The clasts are as much as 20 cm across, and are mainly granitic. Laminae below the largest clasts are strongly depressed. No striated clasts were found.

### Petrography

The sandstone samples from the Mackellar Formation are arkosic to subarkosic (Table 5, Fig. 9) with plagioclase about three times as common as K-feldspar. However, in the Moore Mountains (A002, A005, A008) K-feldspar, some of it microcline, is present in similar proportions to the plagioclase. Most quartz grains are subangular to subrounded, clear and with little or no strain but a few are angular or very well rounded. Chlorite is the most common micaceous mineral and most rock fragments are from low grade metasedimentary rocks. The matrix is mainly micaceous, though some samples have a high proportion of calcite cement.

Size analysis of the coarser beds from the Tillite to the Lowery Glacier (Table 4) shows the most "sandstones" have a mean grain size very close to, and on either side of, the fine sand-coarse silt boundary, and are moderately sorted.

### Primary structures

Most of the sandy beds in the Mackellar Formation are parallel- or microcrosslaminated; medium-scale cross-bedding is rare, but parting lineation was recorded in several of the coarser-grained sandstone units. Asymmetrical ripple marks with sinusoidal cross-sections were found at most localities but were not seen in the Tillite Glacier area

Table 5. Modal analyses (in percent) for samples from the Mackellar Formation

| Sample | Quartz | K-spar | Plag | Lithic | Mica | Calcite | Matrix | Rest |
|---|---|---|---|---|---|---|---|---|
| M302 | 57 | 6 | 15 | 0 | 1 | 0 | 18 | 4 |
| M009 | 41 | 4 | 13 | 0 | 0 | 0 | 39 | 3 |
| Z303 | 70 | 8 | 11 | 0 | 1 | 0 | 8 | 1 |
| L005 | 50 | 3 | 17 | 0 | 7 | 9 | 9 | 4 |
| L009 | 66 | 0 | 7 | 2 | 4 | 4 | 13 | 4 |
| A002 | 48 | 13 | 16 | 2 | 3 | 2 | 7 | 8 |
| A005 | 46 | 12 | 14 | 2 | 5 | 1 | 18 | 2 |
| A008 | 49 | 16 | 15 | 6 | 4 | 0 | 6 | 3 |
| Mean | 53.3 | 7.9 | 13.5 | 1.6 | 3.2 | | 14.9 | 3.8 |
| Standard Deviation | 10.2 | 5.6 | 3.3 | 2.1 | 2.4 | | 11.0 | 2.1 |

Sample with more than 20 percent calcite

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Z301 | 35 | 4 | 13 | 0 | 5 | 37 | 4 | 2 |

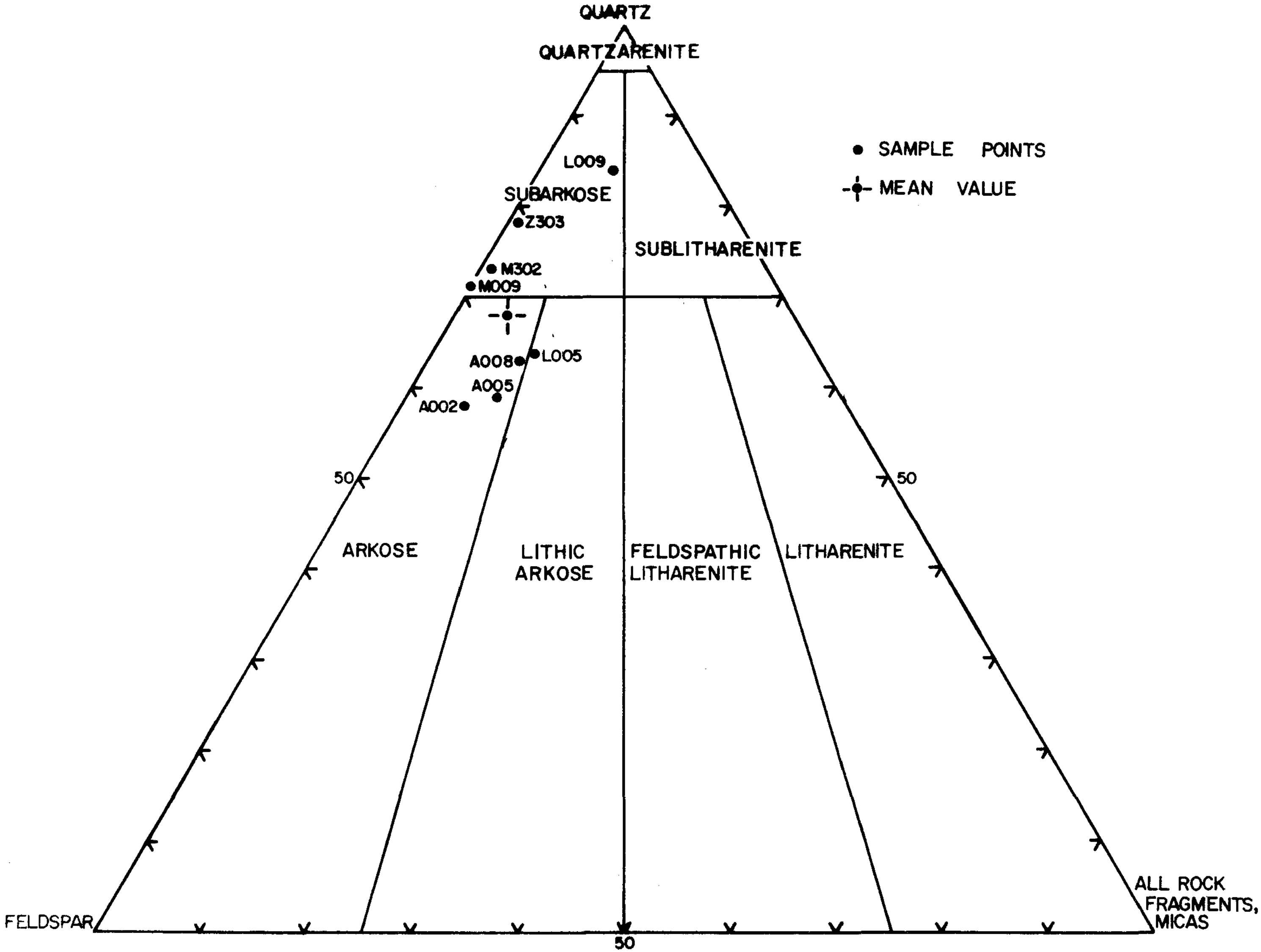



Figure 9. Composition of sandstone samples with less than 20 percent calcite from the Mackellar Formation.

Measurements on 10 sets of ripple marks in the lower part of the formation at LO gave an average wavelength of 27 cm (range 15 to 38 cm), and an average ripple index of 16 (range 8 to 30). Linguoid ripple marks normally about 30 cm across are quite common.

Bulbous sole marks about 0.5 cm deep were found near the base of the formation at LO. There are similar structures in scree fragments from the Mackellar Formation at M1 and ZO, and in a tongue of Mackellar-type strata within the Fairchild Formation at Z3.

Lindsay (1968a,b) has described a mudflow 6.6 m thick within an otherwise normal section of the Mackellar Formation at the western tip of the Moore Mountains. The mudflow unit contains an assemblage of exotic clasts similar to that of tillite in the underlying Pagoda Formation as well as rafts of sandstone apparently derived from the Mackellar Formation itself. More localized penecontemporaneous mass movement is recorded at Mount Weeks (CO), where the lower 3 m of a sandstone unit 50 m above the base of the formation has slumped and rotated. The beds remained more or less coherent during movement and some now dip at as much as 50°. However, 100 m to the south the same sandstone unit has a sharp undeformed sedimentary contact with the unit below. Lesser slumping, with folds as much as 30 cm high, was found at two levels at LO.

## Paleontology

Evidence of life in most of the Mackellar Formation is limited to a few trails about 2mm wide in the middle and upper part of the formation at ZO, Z3 and AO. However, at Mount Weeks (CO) many trails and impressions of at least four varieties (Figs. 10-12) cover the ripple-marked surfaces of a fine-grained thin-bedded sandstone unit that extends from 62 to 73 m above the base of the formation. The steepness of the ridges in the gastropod (?) trails (Fig. 10) suggests that the sand was damp but not saturated with water. It is inferred that the bedding surface was above water for a short time only, and that it was covered with a layer of fine sediment before the sand dried out completely. Some of the surfaces have been disturbed by shallow burrowing (Fig. 13).

## Correlation and age

Units equivalent to the Mackellar Formation have been found in several areas southeast of the Beardmore Glacier (Table 1); these range in thickness from 50 to 300 m. Lithologic descriptions resemble those of the type Mackellar Formation, although black shale is more common in several sections, particularly in the south Queen Maud Range and the Wisconsin Range.

The Mackellar Formation and its equivalents in the central Transantarctic Mountains are thought to be no older than Permian, based

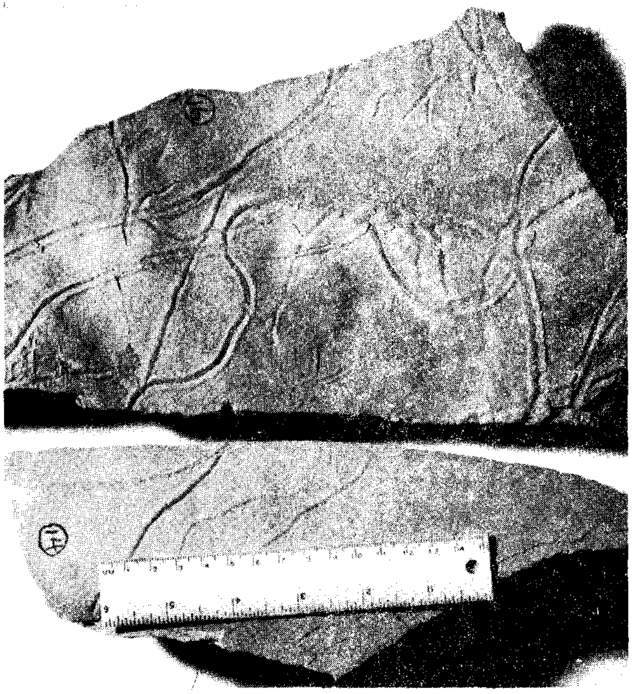


Fig. 10

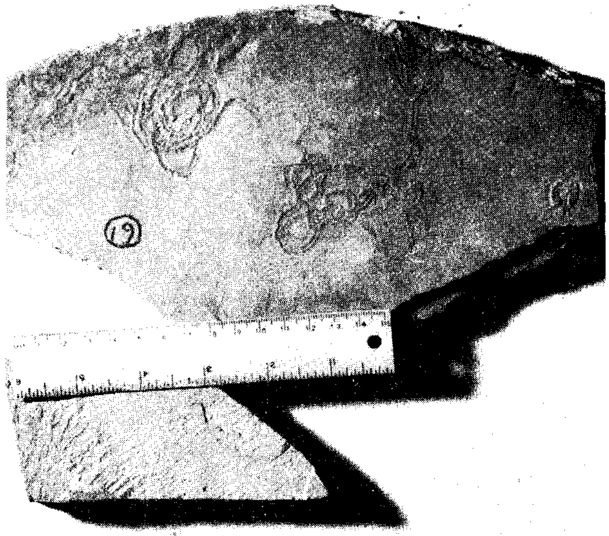


Fig. 11

Figure 10 & 11. Gastropod (?) trails from the Mackellar Formation at Mount Weeks (CO).

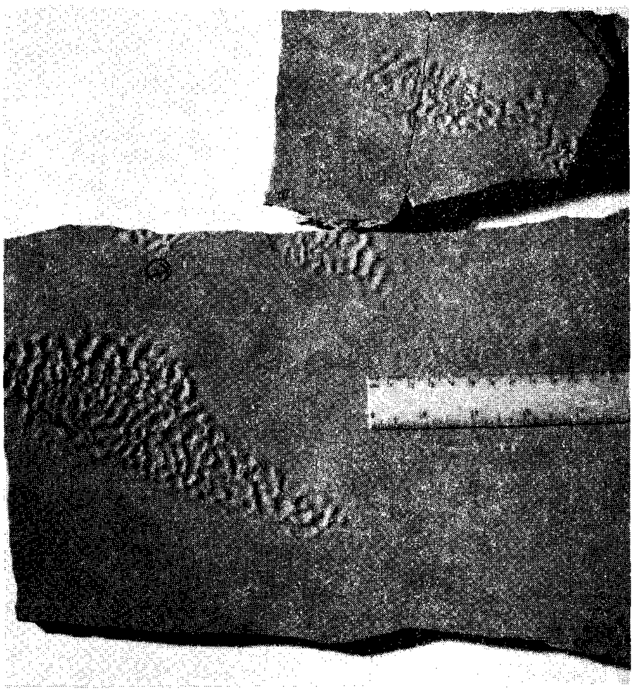


Figure 12. Marks of unknown origin, Mackellar Formation, Mount Weeks (CO).

Figure 13. Burrows and coprolites in the Mackellar Formation, Mount Weeks (CO).

on a recent study of a plant microfossil assemblage from beds equivalent to the Pagoda Formation. According to Schopf (1966, manuscript p. 8), spores from a bedded intra-tillite deposit on Discovery Ridge of the Ohio Range bear close similarity to Nuskoisporites triangularis that Potonié and Lele (1959) identified from the Talchir beds in India. Bisaccate forms compared with Potonieisporites and filicoid spores resembling Granulatisporites orbiculus of Potonié and Lele, also previously reported from the Talchir needle shale in India, are rare. Schopf stated (1966, mansucript p. 13), "The spores from the middle of the tillite still retain a Permian aspect and provide no tangible support for assigning the tillite to the Carboniferous." All known equivalents of the Mackellar Formation are overlain by coal measures that also are Permian (p. 61).

Environment of deposition and source

The dark-colored, fine-grained and moderately-sorted nature of most Mackellar sediment indicates subaqueous deposition in a low energy environment, such as a lake, lagoon or quiet sea, with water circulation at least locally restricted. There is very little change in the typical Mackellar lithology, laminated alternating dark gray to black shale and very-fine-grained sandstone or siltstone, for about 800 km southeast of the Lennox-King Glacier. The shale normally is dominant. Northwest of the Lennox-King Glacier, however, the Mackellar Formation contains more and coarser-grained sandstone, light-colored siltstone replaces dark shale, and erosion surfaces are present. The formation pinches out farther to the northwest between the Nimrod and Darwin Glaciers. These changes indicate that the strandline of the Mackellar basin was located between the Lennox-King and Nimrod Glaciers much of the time. Analysis of ripple marks in the Mackellar Formation at Mount Weeks by Lindsay (1968a, p. 61) indicated that the ripples formed in the swash zone, and the observation concerning the trails in the same strata (this report, p. 20) suggests that some beds were exposed to the air. The regional paleocurrent flow was to the southeast (Fig. 4), both in the inferred transitional zone and in the submarine part of the basin as far southeast as the Wisconsin Range (Barrett, 1965; Minshew, 1967).

Two lines of evidence support a fresh or brackish body of water for the depositional environment of the Mackellar Formation and its equivalents at least as far south as the Axel Heiberg Glacier;

(1) the limited indications of animal life in the strata, and

(2) the high $Sr^{87}/Sr^{86}$ ratios for limestones from the Mackellar Formation, like those from the definitely non-marine Buckley Formation (Barrett and others, 1968c). The $Sr^{87}/Sr^{86}$ ratios indicate that there was not free exchange between waters of the Mackellar basin and the Permian oceans.

A point previously considered to favor a marine environment of deposition for the Mackellar Formation is its lack of lithologic variation and its vast extent, suggesting deposition in an extremely large body of water. However, Minshew (1968) has recently pointed out the similarity in lithology and extent of the Mackellar and equivalents to the southeast with the largely non-marine sediments of the Baltic Sea and Gulf of Bothnia, a body of water 1500 km long an average of 300 km wide in which salinities over most of the area are less than half that of the open oceans. A long narrow basin of deposition is also consistent with the unimodal paleocurrent pattern.

The mineralogy of the sandstone samples suggest a granitic and quartzose metamorphic and sedimentary source, the detritus coming from a terrain much more quartzose that the pelitic schist that presently underlies most of the Beardmore Glacier area.

## Fairchild Formation

### Definition

The name Fairchild Formation is here proposed for cross-bedded fine- to medium-grained sandstone that overlies the Mackellar Formation, and is overlain by the *Glossopteris*-bearing coal measures in the Beardmore Glacier area. The formation is named from Fairchild Peak (2180 m), near the mouth of the Tillite Glacier, and the unit is typically exposed on the ridge that runs from Fairchild Peak up to Mount Mackellar. The formation is 146 m thick at the type section (M1, Appendix I), which is a rock buttress on the northwest face of Mount Mackellar (Fig. 14) 4.8 km northwest of the summit at 83° 56.8' S; 166° 29' E. Strata here included in the Fairchild Formation were first described by Grindley (1963) as the lower part of the Buckley Coal Measures, but have been set apart because of their distinctive massive character and lack of coal or carbonaceous shale.

The lower contact of the formation at the type section is placed at the base of the lowest thick bed of massive medium-grained sandstone. The strata below this are fissile fine-grained sandstones; massive sandstone is the dominant lithology above, though thin very-fine-grained sandstone beds as much as a meter thick persist for about 10 m above the contact. The contact of the Fairchild Formation with the overlying coal measures is the base of the lowest sandstone containing white rounded quartz pebbles.

### Distribution and thickness

The Fairchild Formation, like the Mackellar Formation, crops out in a belt extending north from Buckley Island to Mount Miller and west to the Moore Mountains. The formation thins to the east and southeast, from over 200 m in the Moore Mountains to 136 m at Mount Miller

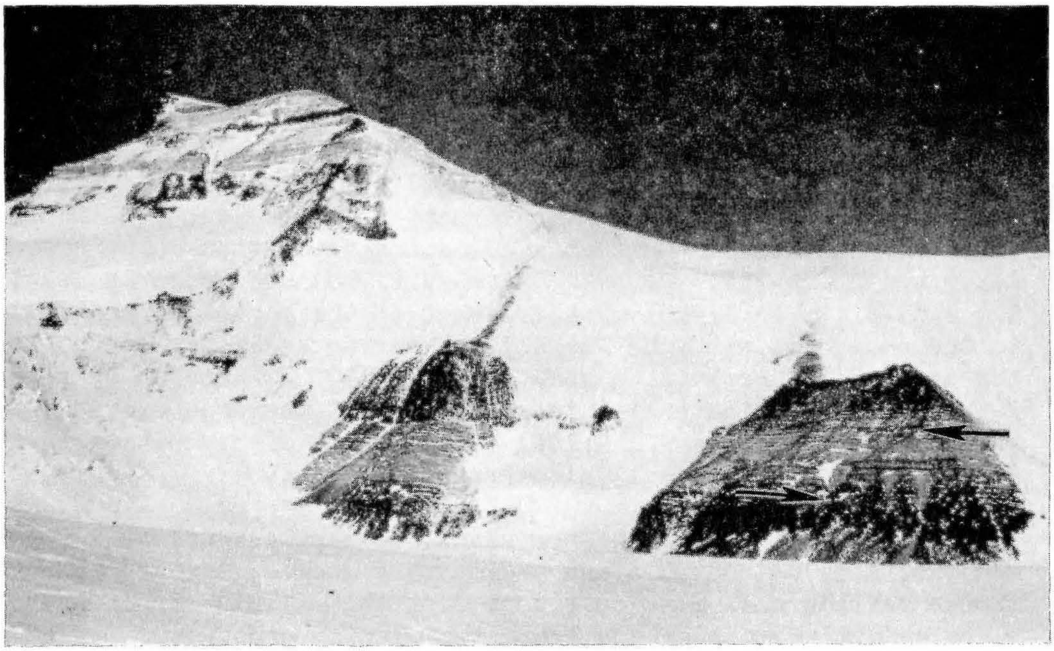


Figure 14. North face of Mount Mackellar, northern Queen Alexandra Range. Upper and lower contacts of the type section of the Fairchild Formation are arrowed. Diabase sills form the steep bluffs.

Figure 15. Looking west at the Mackellar and Fairchild Formations at LO from the Pagoda-Mackellar contact. The top of the Fairchild Formation, though not exposed here, is thought to be close to the top of the ridge.

and 128 m near Mount Mackellar. However, near Mount Wild, 160 km south of the Moore Mountains, the unit is at least 198 m thick, and on nearby Buckley Island equivalent beds are 222 m thick (Young and Ryburn, 1968).

Lower contact

The base of the Fairchild Formation, which is well-exposed at many places between the Tillite Glacier and the Moore Mountains, is sharp, although stringers of Mackellar-type shale are common in the lowest part of the formation in northwest, the change in lithology across the contact is normally more abrupt; near Clarkson Peak (Z2) and in the Moore Mountains (A3, A4) the lower contact is an erosion surface overlain by sandstone with shale fragments near the base.

Lithology

Most of the Fairchild Formation consists of a light-gray fine- to medium-grained sandstone that weathers light gray or light reddish brown. The lower part of the formation typically forms bluffs (Fig. 15), and the upper part, which commonly includes beds of fissile very-fine-grained sandstone and shale, forms slopes. Shale and fine-grained sandstone fragments, some more than 30 cm across, were found at a number of localities in the middle and upper parts of the formation.

Sections at Mount Wild (B0) and in the Queen Elizabeth Range have considerably more carbonaceous material, in the form of laminae, small fragments, stems, or (especially at L0) coal streaks, than other sections in the area.

Rounded exotic clasts become increasingly common in the Fairchild Formation toward the northwestern part of the area. None were found in the Holland or northern Queen Alexandra Ranges, but a quartz and a quartzite pebble were noted near the base of the formation near Mount Wild (B0) and 35 pebbles were recovered from a similar level at Turnabout Ridge (L0). In the Moore Mountains and at Mount Weeks pebbles are common in the lower 50 m of the formation, both scattered through the sandstone and as stringers. Similar isolated pebbles occur higher in the formation at most sections examined in the Moore Mountains area.

Most of the pebbles from Turnabout Ridge and the Moore Mountains are of quartzose metasedimentary rocks (Table 6), in contrast to both the varied pebble lithologies of the underlying Pagoda Formation, and the rounded white quartz pebbles that characterize the Buckley Formation and define its base (p. 33). Most of the Fairchild pebbles are moderately well rounded. They normally range from 2 to 10 cm in diameter but some in the Moore Mountains are as much as 30 cm across. Because of their localized distribution, rounding and dominance of quartzose metasedimentary lithologies, it is suggested that the source rock was a quartzite-dominated conglomerate some tens of kilometers

Table 6. Lithologies of pebbles from the Fairchild Formation in the Moore Mountains (A014) and Turnabout Ridge (L014); from six beds in the Pagoda Formation at the base of section AO, Moore Mountains (from Lindsay, 1968a); and from five samples of quartz pebble beds at and near the base of the Buckley Formation (B011, Z022, Z318A, L105, L108). Numbers of pebbles are in parentheses

| Sample Number | Quartzite* | Graywacke | Schist+ | Quartz | Chert | Limestone | Granite Gneiss | Volcanic |
|---|---|---|---|---|---|---|---|---|
| A014 | 74 | 7 | 2 | 7 | 4 | - | 6 | - (100) |
| L014 | 74 | - | 3 | 11 | 9 | - | - | 3 (35) |
| Pagoda Formation | tr | 30 | 6 | 6 | 11 | 6 | 40 | x (877) |
| Buckley Formation | 5 | 3 | tr | 88 | - | - | 1 | 1 (352) |

*includes several varieties of quartzose and feldspathic sandstone

+includes argillite

northwest of the Moore Mountains. Laird and others (in preparation) report a conglomerate of quartzite pebbles in basement rocks 40 km to the northwest, but Adamson and others (in preparation) have recorded quartzite pebbles at about this stratigraphic position even further to the northwest in the Geologists Range.

### Petrography

The Fairchild Formation consists mainly of arkose and subarkose (Table 7, Fig. 16), feldspar being one-third to one-half as common as quartz. K-feldspar, some of it with microcline twinning, is as common as plagioclase in most of the section, but decreases markedly in proportion to plagioclase near the top of the formation. The lithic fragments are from low grade metasedimentary rocks. Cloudy reddish brown biotite, probably from a similar source, is the most common mica. Most heavy mineral grains are garnet. The matrix is mainly sericitic but a few samples are calcite-cemented.

As in the Mackellar Formation, most of the quartz grains in thin sections of sandstone appear subangular to subrounded, but a few are very well rounded. The latter probably were derived from the Alexandra Formation, which also supplied large quantities of quartz sand to the lower part of the Pagoda Formation (Lindsay, 1968a).

The mean grain sizes are mainly in the fine sand range, and the sorting is good (Table 4, p. 14).

### Primary structures

Much of the Fairchild Formation is parallel-bedded, and parting lineation is widespread, but intervals about 10 m thick containing sets of medium-scale cross-bedding about 0.5 m thick are common. Microcrosslamination generally occurs in much thinner units, about 2 m thick, mostly in the lower few meters or the upper 30 m of the formation. Low-angle discordant bedding is widespread, and is particularly well developed near Mount Wild and in the Queen Elizabeth Range where there are broad scours at least 15 m across and 3 m deep, with shale and fine-grained sandstone fragments more than 30 cm across at the base. A channel 2.4 m wide and 0.6 m deep (Fig. 17) has been cut in white medium-grained sandstone near the base of the formation near Clarkson Peak. The channel is filled with greenish-gray fine-grained sandstone in which the bedding laps against the channel walls. A number of broad scour surfaces in the Moore Mountains are covered by thin patches of lag gravel composed of quartzite pebbles (p. 25). At A4 the base of the channel is exposed as a bench (Fig. 18). The lower meter of channel fill is gritty sandstone with patches of pebbles as much as 30 cm across near the base; the upper 2 m, which is gray very-fine-grained sandstone in which the upper 30 cm is slumped and brecciated, probably represents quiet water deposition in a local cut-off of the stream. The fill pinches out within 15 m on either side of the channel axis.

Table 7. Modal analyses (in percent) for samples from the Fairchild Formation

| Sample | Quartz | K-spar | Plag | Lithic | Mica | Calcite | Matrix | Rest |
|---|---|---|---|---|---|---|---|---|
| B001 | 36 | 14 | 25 | 1 | 4 | 0 | 14 | 5 |
| B002 | 41 | 11 | 25 | 2 | 5 | 0 | 12 | 4 |
| B003 | 55 | 11 | 11 | 1 | 0 | 3 | 16 | 2 |
| B006 | 44 | 6 | 27 | 1 | 6 | 3 | 10 | 3 |
| B010 | 53 | 4 | 20 | 1 | 1 | 0 | 20 | 1 |
| M104 | 57 | 8 | 15 | 2 | 2 | 0 | 14 | 3 |
| M105 | 67 | 10 | 12 | 1 | 0 | 1 | 8 | 2 |
| M107 | 64 | 15 | 11 | 3 | 0 | 0 | 5 | 2 |
| M108 | 53 | 16 | 19 | 2 | 0 | 0 | 7 | 2 |
| M109 | 56 | 9 | 21 | 2 | 1 | 0 | 8 | 3 |
| M112 | 71 | 6 | 11 | 2 | 1 | 1 | 6 | 3 |
| Z013 | 64 | 13 | 11 | 5 | 1 | 0 | 4 | 1 |
| Z015 | 65 | 9 | 9 | 3 | 1 | 0 | 11 | 2 |
| Z017 | 67 | 5 | 9 | 4 | 1 | 0 | 10 | 4 |
| Z018 | 62 | 6 | 14 | 3 | 2 | 0 | 9 | 4 |
| Z020 | 80 | 1 | 5 | 4 | 1 | 0 | 7 | 2 |
| Z304 | 74 | 8 | 6 | 2 | 0 | 0 | 5 | 3 |
| L011 | 58 | 9 | 6 | 5 | 2 | 11 | 9 | 1 |
| L012 | 69 | 9 | 5 | 3 | 0 | 0 | 13 | 2 |
| L013 | 69 | 11 | 6 | 2 | 0 | 8 | 3 | 1 |
| L018 | 53 | 9 | 18 | 1 | 4 | 0 | 11 | 3 |
| L103 | 55 | 5 | 17 | 1 | 2 | 0 | 17 | 3 |
| L104 | 44 | 1 | 18 | 1 | 10 | 0 | 23 | 3 |
| A010 | 52 | 19 | 13 | 2 | 2 | 5 | 6 | 3 |
| A013 | 48 | 16 | 18 | 3 | 0 | 0 | 11 | 3 |
| A016 | 57 | 6 | 18 | 0 | 3 | 2 | 11 | 5 |
| Mean | 58.2 | 9.2 | 14.2 | 2.2 | 2.0 | | 10.4 | 2.6 |
| Standard Deviation | 10.7 | 4.6 | 6.5 | 1.3 | 2.4 | | 4.9 | 1.0 |

Sample with more than 20 percent calcite

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| A015 | 35 | 13 | 13 | 2 | 2 | 31 | 0 | 4 |

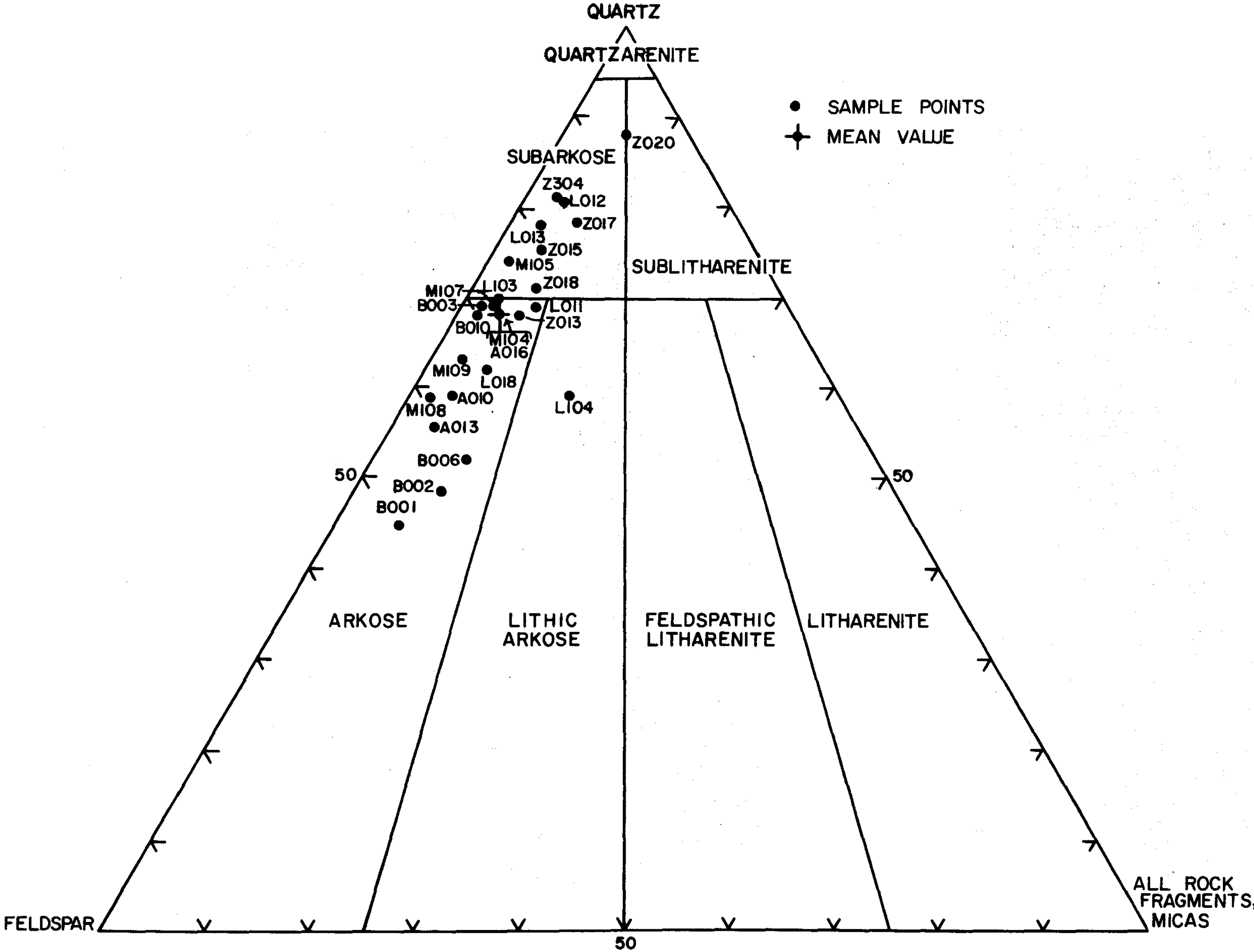



Figure 16. Composition of sandstone samples with less than 20 percent calcite from the Fairchild Formation.

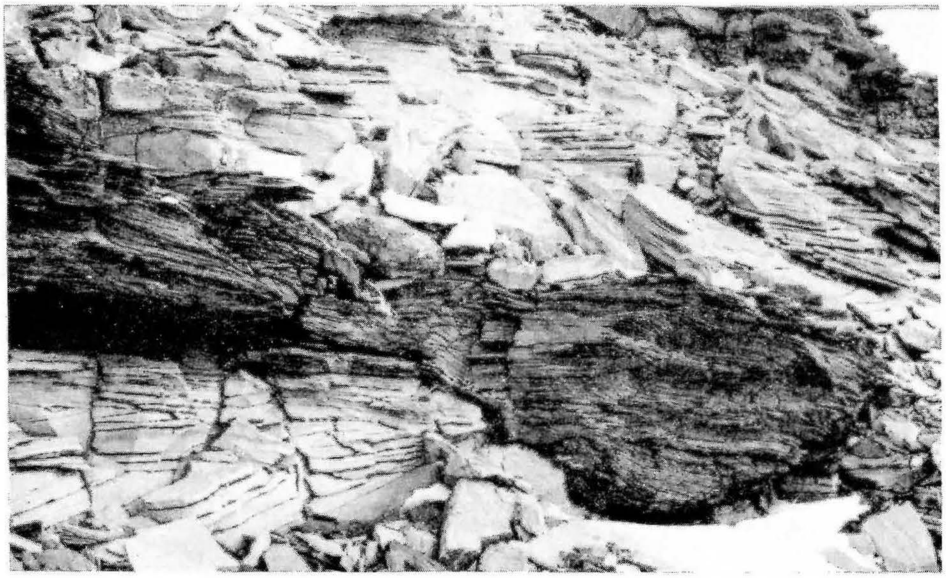


Figure 17. Channel 5 m above the base of the Fairchild Formation near Clarkson Peak (Z3). Bedding laps against the channel walls.

Figure 18. This platform is the floor of a stream channel 17 m above the base of the Fairchild Formation at A4, Moore Mountains. The stream flowed from upper left to lower right. The channel axis is about 15 m to the left (west) of the photograph, but the fine-grained channel fill extends only just into the photographed area because here it has been partly eroded and replaced by a later channel sandstone (center).

At Clarkson Peak microcrosslamination and linguoid ripple marks are common within a tongue of Mackellar-type beds in the Fairchild Formation. This tongue includes a 4-m-thick sequence of thin-bedded sandstone. Fine-grained sandstone beds, each several centimeters thick with sole-marked lower surfaces, alternate with laminated very-fine-grained sandstone beds of similar thickness. Within the sole-marked strata a set of 10-cm-high slump folds lean to the south approximately in the direction of the regional paleoslope and give proof of small-scale penecontemporaneous mass movement. The asymmetrical form of some sets of sole marks, which lie in rows, can be seen in sections perpendicular to the strike of the rows. The direction in which the sole marks lean is about that of the slump folds described above. The sole marks may have formed by sediment loading and differential compaction but they seem to have been influenced by slight mass movement related to the slope of the depositional surface. Similar sole marks and a set of dessication cracks were found in slabs of float material from the immediately overlying beds.

### Paleontology

The only identifiable fossil remains from the Fairchild Formation of the Beardmore Glacier area are leaf impressions of *Gangamopteris* sp. (cf. *G. obligua* McCoy) (identified by Dr. J. M. Schopf, U.S.G.S. Coal Geology Laboratory, Ohio State University) collected by Ralph Baillie and the writer from the Moore Mountains (AO). The leaf impressions (Schopf coll. no. Ant-67-8-150) are from a pebble-bearing sandstone unit 24 m above the top of the Mackellar Formation and 120 m above the Pagoda Formation. The leaves are associated with a great deal of carbonified stem material, which is widespread throughout the Fairchild Formation in the northwestern part of the Beardmore Glacier area.

### Correlation and age

Strata equivalent to the Fairchild Formation have been reported from Buckley Island by Young and Ryburn (1968), who described the lower part of the Buckley Coal Measures as consisting of 222 m of massive sandstone overlying the Mackellar Formation. Laird and others (in preparation) state that, at the head of the Nimrod Glacier, "the basal 800 ft. [240 m] of the [Buckley Coal Measures] formation is made up of cross-bedded, coarse, yellow sandstone containing carbonaceous fragments." In both investigations, the Mackellar Formation was recognized but none of the investigators reported the presence of quartz pebbles within the coal measures. The 167-m-thick unit of "buff-colored, fine- to coarse-grained sandstone..." placed by Wade and others (1965) in the Mackellar Formation is also considered equivalent to the Fairchild Formation. The relationship of these to equivalent units in more distant areas is shown in Table 1 (p. 7).

The age of the Fairchild Formation is defined by the same limits as were established for the Mackellar Formation. *Gangamopteris* near the base of the Fairchild Formation does little to better define the age of the formation, presumably Permian, although it is stratigraphically the lowest known occurrence of an element of the *Glossopteris* flora in Antarctica.

### Environment of deposition and source

Layers of intraformational clasts, as well as the occasional broad scours and exotic clasts in the northwestern part of the area, indicate deposition in an environment in which strong currents were common, and point to fluvial deposition. The dominance of sandstone in the section shows that the quantities of sand were readily available and the abundance of carbonaceous material (including stems) indicates a nearby non-marine environment. It is suggested that the formation was deposited by aggrading streams on an alluvial plain. The immature mineralogy, indicated by the high feldspar content, and the generally poor rounding of the sand grains indicates deposition and burial with minimal reworking. The source area, as for the Mackellar Formation, was largely granitic and contained more quartzose sedimentary and metasedimentary rocks than the local pelitic basement includes. The immediate source of the sand is thought to have been the large reservoir of rock debris left by the Pagoda glaciation(s). No large topographic highs are known to have existed at this time for at least 1000 km north-northwest of the Beardmore Glacier. However, the possibility of a supply of fresh detritus from orogenic belts marginal to the present limits of available outcrop in the sourceward direction cannot be completely discounted.

## Buckley Formation

### Definition

Grindley (1963) gave the name Buckley Coal Measures to the Permian coal-bearing beds of the Beardmore Glacier area, and designated as the type section the strata exposed from the ice level of the Beardmore Glacier above Lizard Point to the top of Mount Wild. The name was taken from Buckley Island, about 16 km to the southeast, where the coal measures were discovered by Frank Wild of the 1907-09 British Antarctic Expedition. The lower part of the Buckley Coal Measures of Grindley has been set apart in this paper as a separate formation, the Fairchild Formation. It is proposed that the name Buckley Formation be applied to the remaining upper part of the Buckley Coal Measures, that is, to the coal-bearing strata, and that the type section be part of that designated by Grindley, beginning 200 m above the ice level of the Beardmore Glacier at the level at which quartz pebbles are present

(Fig. 19). The upper contact has been eroded away at the type locality, but was found to the north, near the head of the Wahl Glacier (W1). East of the Beardmore Glacier carbonaceous beds of the Buckley Formation are overlain disconformably by subarkosic sandstone and noncarbonaceous greenish-gray mudstone of the Fremouw Formation.

Distribution and thickness

The Buckley Formation is widely distributed in the Beardmore Glacier area, but a complete section has yet to be measured. The lower 300 m of the formation are exposed near Mount Wild at the type section (B0-B2) and in the Holland Range (Z0, Z3). The upper 250 to 350 m of the formation are exposed in the central Queen Alexandra Range (W0, W1) and between the heads of the Beardmore and Ramsey Glaciers. Thicker sections were measured around the Bowden Névé, the thickest being a total of 745 m by combining two sections (L1, L2) near the head of the Lowery Glacier. Although the upper contact was not found, boulders of white medium- to coarse-grained quartzose sandstone were discovered in the snow at the top of section L2; the mineral composition of the sandstone forming the boulders (p. 57) is very similar to that of the basal subarkose of the Fremouw Formation. If the correlation of L1 and L2, which are 15 km apart but intruded by the same sill, is correct, 745 m is probably close to the true thickness of the Buckley Formation in this area.

Lower contact

The base of the Buckley Formation is placed at the base of the lowest quartz-pebble-bearing sandstone in the Permian post-glacial section of the Beardmore Glacier area. The rounded white quartz pebbles (Fig. 20) appear in the section in about the same stratigraphic position within the transition zone between the Fairchild Formation and equivalents (a massive sandstone from 100 to 200 m thick) and the overlying coal measures everywhere over a distance of 1000 km from the Queen Elizabeth Range (C0) to the Ohio and Wisconsin Ranges (Long, 1959; Minshew, 1966).

The lowest white rounded quartz pebbles near the base of the Buckley Formation in the Moore Mountains and at Painted Cliffs are scattered through a greenish-gray laminated siltstone 24 to 27 m above the base of a medium- to coarse-grained gritty sandstone. The pebble-bearing siltstone horizon also is found 24 m above the lowest quartz pebble horizon that defines the top of the Fairchild Formation at the type section in the Tillite Glacier area (M1). The gritty sandstone is taken as the base of the Buckley Formation in the Moore Mountains and at Painted Cliffs because such sandstone seems to occur at about the same horizon as the lowest pebbles in the Tillite Glacier area.

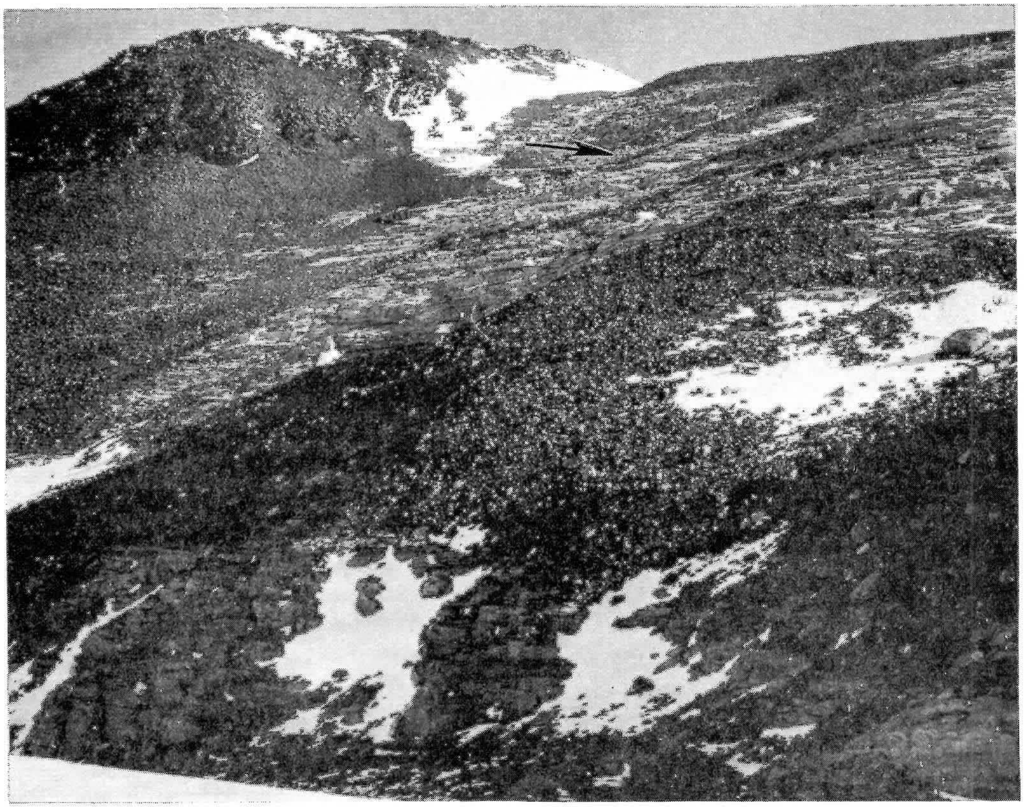
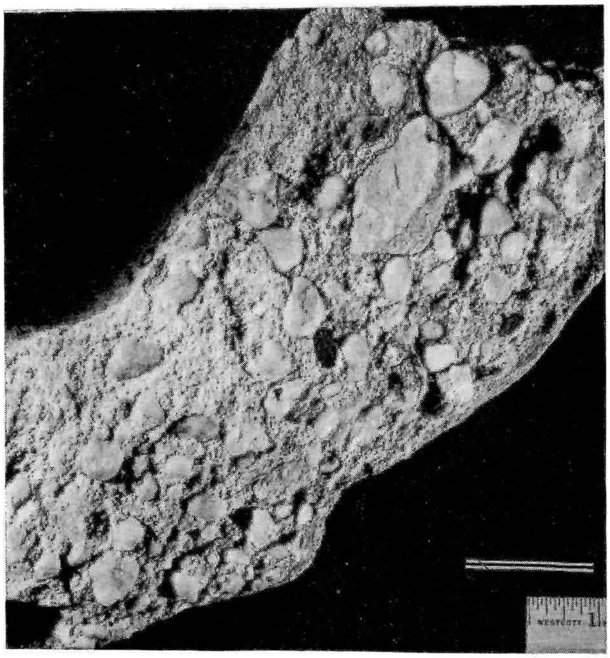


Figure 19. The Fairchild and the lower part of the Buckley Formation at BO on the west side of the Beardmore Glacier, above Lizard Point, looking west. The arrow indicates the base of the type Buckley Formation.

Figure 20. (lower left). Rounded white quartz pebbles in a sand matrix from the base of the Buckley Formation near Mount Mackellar (M2). Bar is 5 cm long. Photo - OSU



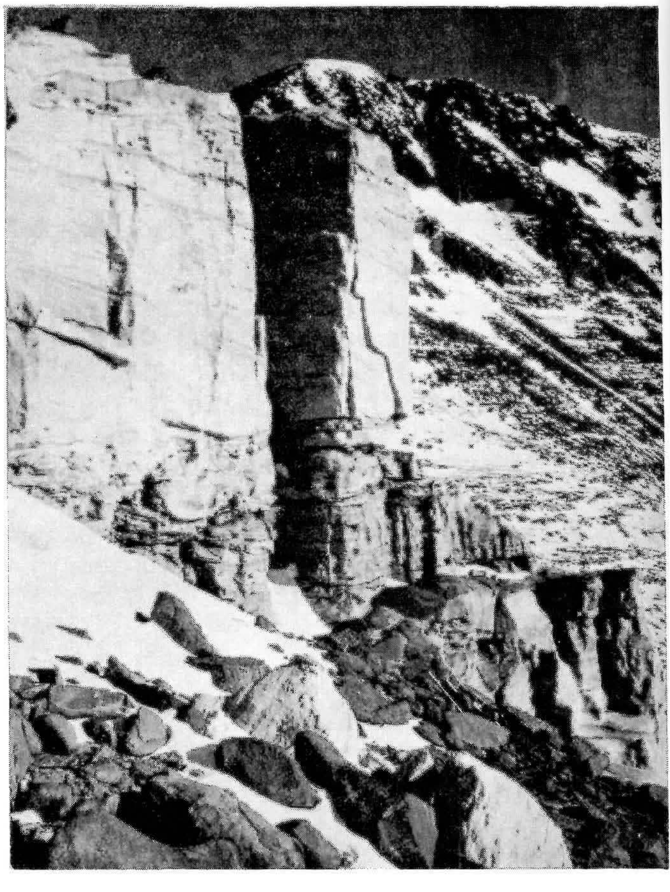


Figure 21. (right). Light-colored gritty sandstone overlies darker fine- to medium-grained sandstone in the Moore Mountains (A2). The contact marks the base of the Buckley Formation in the Queen Elizabeth Range.

Although the formational contact is sharp, change in gross lithology in many places is gradual. In some localities the dark shale beds typical of the coal measures appear as much as 24 m below the contact; at other localities the lowest dark shale is as much as 20 m above the base of the formation.

Lithology

The Buckley Formation consists of a crudely cyclic sequence of arkosic-subarkosic and lithic (volcanic) sandstone, carbonaceous shale and mudstone, and minor coal. Both nonvolcanic and volcanic sandstone beds typically overlie an erosion surface, and grade upward into carbonaceous shale. The sandstone weathers light greenish gray or reddish brown, is fine to medium grained, and includes stringers and laminae of greenish-gray fissile very-fine-grained sandstone. Shale fragments, mostly 3 or 4 cm across but some as much as 40 cm across, commonly are concentrated in the lower 30 cm of the sandstone bed. Logs and stem fragments as much as 30 cm across are less common, though two or three large concentrations of logs were found in most of the thicker sections measured.

Most shale in the Buckley Formation is medium gray to black, and coaly in a few places. Greenish-gray shale is much less common. Thin lenses of white-weathering light or medium-gray blocky mudstone, in which some of the best-preserved plants are found, appear in the upper part of the formation. They are uncommon northwest of the Beardmore Glacier, but form a considerable part of the upper 200 m of the formation at Graphite Peak and McIntyre Promontory to the southeast.

The lower part of the formation contains a much higher proportion of sandstone than the middle and upper parts. In the lower part, which ranges in thickness from 55 m at Painted Cliffs to 124 m on the Lowery Glacier, fine- to medium-grained sandstone comprises about 70 percent of the section. The middle and upper parts of the formation are about 30 percent sandstone. However, at Mount Miller, massive cliff-forming volcanic sandstone at least 200 m thick (Figs. 22, 23) seems to make up the entire upper part of the formation. The sandstone was reached with some difficulty and then could be sampled only in the lower 40 m (Z040-42), which contain a number of log impressions. Binocular examination failed to reveal any persistent shale units higher on the mountain.

The quartz pebbles in the Buckley Formation are rounded, subspherical, and generally range in diameter from 1 to 5 cm (Fig. 21), although some are as much as 25 cm across. Associated pebbles of other lithologies normally form about 10 percent of the total pebbles (Table 6). In the Tillite Glacier area, and at Z3 and L1, the pebbles are scattered through sandstone in the lower 24 to 40 m of the formation. At BO, ZO, PO, CO, and DO, they are in a single bed at or near the base of the formation, and at BO, PO and in the Moore Mountains the pebbles are very

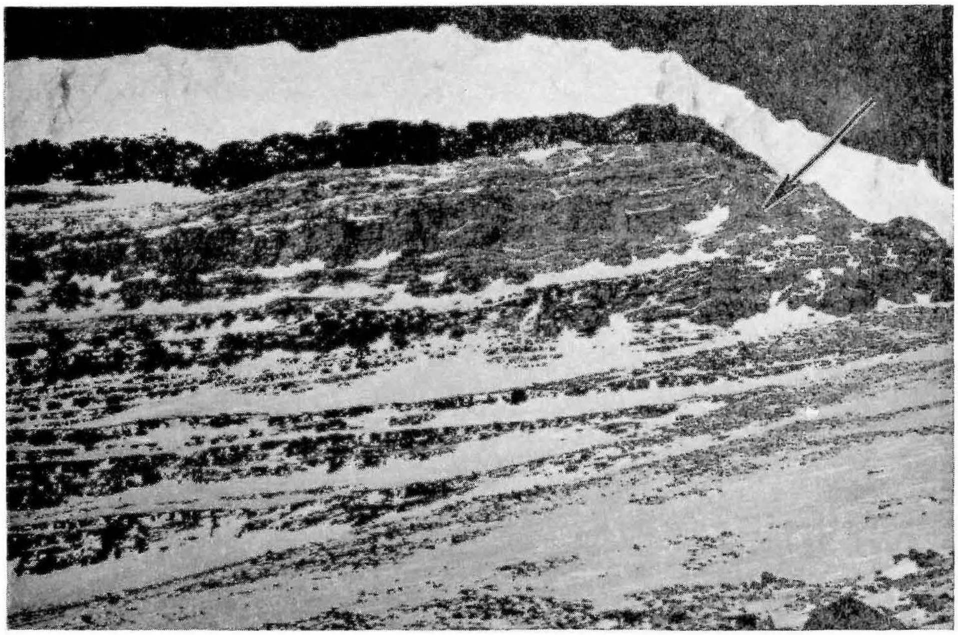
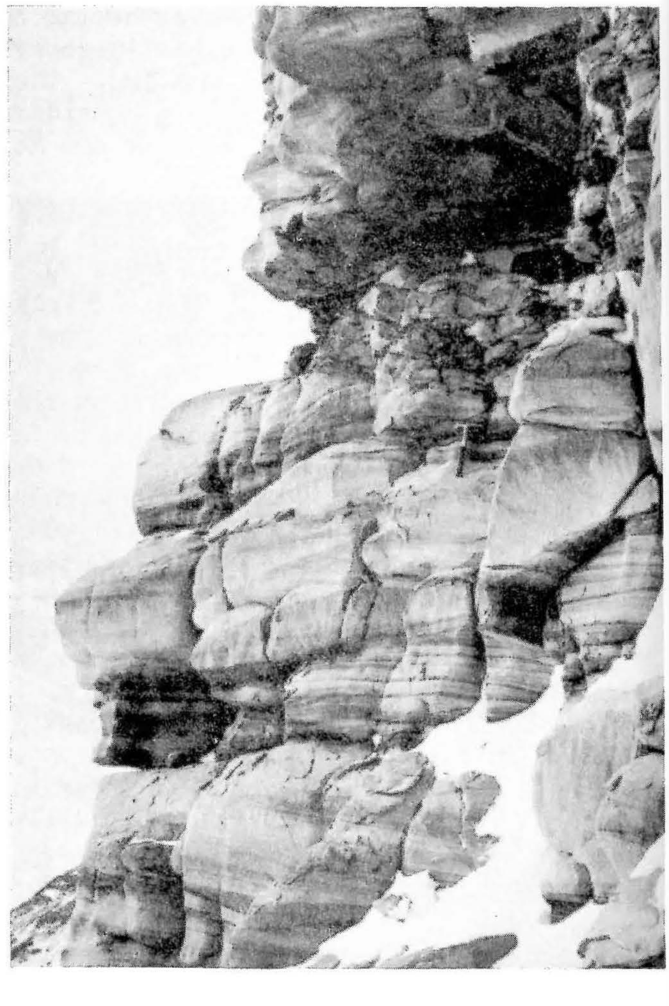


Figure 22. Strata from 150 to 520 m above the base of the Buckley Formation high on the southeast face of Mount Miller, capped by a diabase sill and ice cliffs. The site of Figure 23 is arrowed.

Figure 23. Bedded volcanic sandstone that forms the light-colored cliffs in Figure 22. The dark patches under the overhang are log and stem impressions.



scarce. A few thin concentrations of similar quartz pebbles, mostly less than 4 cm but with some as much as 10 cm across, also occur locally in the middle and upper parts of the formation throughout the area. The pebbles are particularly common near the base of beds of quartzose sandstone 220 to 175 m below the top of the formation at McIntyre Promontory.

Coal normally forms less than one percent of the section in the lower part of the formation and at some localities is absent. Coal beds were recorded in the middle and upper parts of the formation in 10 of the 12 sections measured and in the southwest part of the area coal comprised 3 to 6 percent of most sections (C3, P1, R0, B2). At Mount Wild (B2) there is at least 10.7 m of coal in the formation, mostly in a bed 8.5 m thick and 36 m below the summit of Mount Wild. Probably more was once present, for several bodies of graphite as much as three meters thick were found in a dolerite-intruded and brecciated zone from 150 to 210 m above the base of the formation at B1. Graphite was found also at Graphite Peak (where it has been previously recorded by McGregor, 1965) and near the base of the McIntyre Promontory section. At Painted Cliffs (P1) there is a total of about 15 m of coal, including one bed 10.7 m thick, all from 380 to 480 m above the base of the formation.

Most analysed Antarctic coal samples are of low-volatile bituminous or semianthracite rank (Schopf and Long, 1966). The four coal samples from the Buckley Formation of the Queen Elizabeth Range (Table 8) are low-volatile bituminous, but the sample from Graphite Peak, while still bituminous, is of somewhat lower rank.

Varvoid lamination was first reported from the Permian coal measures of the Beardmore Glacier area by Gunn and Walcott (1962, p. 422 and Fig. 6). They described "regular, graded laminations, each about 4 mm thick" in 30 cm of claystone in a section on Bengaard Nunatak, 16 km west of Clarkson Peak. Mudstone, about 1 m of which has varvoid lamination, was found by this writer 250 and 400 m above the base of the Buckley Formation on Mount Picciotto (P1), and 360 m above the base of the formation on Mount Miller. The laminae at Mount Picciotto (Fig. 24) are similar in thickness and regularity to those figured by Gunn and Walcott, but those at Mount Miller range from 0.8 to 4 mm in thickness and average only 1.4 mm per lamination.

### Petrography

Sandstone samples from the Buckley Formation (Table 9, Fig. 25) fall into two major groups -- arkosic-subarkosic and lithic (volcanic) sandstones. Samples from the lower part of the formation are all subarkosic or arkosic, but in the middle and upper parts of the formation volcanic sandstone (sandstone in which more than 10 percent of the fragments are of volcanic origin) generally is more common. The lowest volcanic sandstone is from 100 to 300 m above the base of the formation

Table 8. Analyses of coal samples after crushing and removing the fraction heavier than 1.6 grams/cc. The samples were submitted by Dr. J. M. Schopf, U. S. Geological Survey, Columbus, to the U. S. Bureau of Mines, Coal Analysis Section. Sample numbers in parentheses are those of U. S. Geological Survey, Columbus.

| Sample | Formation | Condition | Proximate Analysis | | | | Ultimate Analysis | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Moisture | Volatile matter | Fixed Carbon | Ash | H | C | N | O | S | Ash | B.t.u. |
| A321 (CGL-300) | Buckley | As received | 2.9 | 14.8 | 74.2 | 8.1 | 2.7 | 77.0 | 1.9 | 9.8 | 0.5 | 8.1 | 12,250 |
| | | Moisture free | | 15.3 | 76.4 | 8.3 | 2.4 | 79.4 | 1.9 | 7.5 | 0.5 | 8.3 | 12,620 |
| | | Moisture & ash free | | 16.6 | 83.4 | | 2.6 | 86.6 | 2.1 | 8.1 | 0.6 | | 13,760 |
| C203 (CGL-292) | Buckley | As received | 3.5 | 12.2 | 77.4 | 6.9 | 2.9 | 78.1 | 1.9 | 9.4 | 0.8 | 6.9 | 12,600 |
| | | Moisture free | | 12.6 | 80.2 | 7.2 | 2.6 | 80.9 | 1.9 | 6.6 | 0.8 | 7.2 | 13,050 |
| | | Moisture & ash free | | 13.6 | 86.4 | | 2.8 | 87.1 | 2.1 | 7.1 | 0.9 | | 14,070 |
| R005 (CGL-297) | Buckley | As received | 3.6 | 14.2 | 74.4 | 7.8 | 2.5 | 75.6 | 1.9 | 11.5 | 0.7 | 7.8 | 12,010 |
| | | Moisture free | | 14.7 | 77.2 | 8.1 | 2.2 | 78.4 | 2.0 | 8.6 | 0.7 | 8.1 | 12.450 |
| | | Moisture & ash free | | 16.0 | 84.0 | | 2.4 | 85.3 | 2.2 | 9.3 | 0.8 | | 13,550 |
| R008 (CGL-298) | Buckley | As received | 2.8 | 12.1 | 74.5 | 10.6 | 2.7 | 74.9 | 1.9 | 8.9 | 1.0 | 10.6 | 11,970 |
| | | Moisture free | | 12.5 | 76.6 | 10.9 | 2.4 | 77.0 | 1.9 | 6.8 | 1.0 | 10.9 | 12,310 |
| | | Moisture & ash free | | 14.0 | 86.0 | | 2.7 | 86.4 | 2.2 | 7.5 | 1.2 | | 13,810 |
| R014 (CGL-299) | Buckley | As received | 0.8 | 6.2 | 38.0 | 55.0 | 0.9 | 39.6 | 0.7 | 3.6 | 0.2 | 55.0 | 5,960 |
| | | Moisture free | | 6.2 | 38.4 | 55.4 | 0.8 | 39.9 | 0.7 | 3.0 | 0.2 | 55.4 | 6,010 |
| G012 (CGL-295) | Buckley | As received | 7.9 | 23.1 | 47.6 | 21.4 | 2.0 | 52.7 | 1.2 | 22.3 | 0.4 | 21.4 | 7,430 |
| | | Moisture free | | 25.1 | 51.7 | 23.2 | 1.2 | 57.2 | 1.3 | 16.7 | 0.4 | 23.2 | 8,060 |
| | | Moisture & ash free | | 32.7 | 67.3 | | 1.6 | 74.5 | 1.7 | 21.7 | 0.5 | | 10,490 |
| F328 (CGL-296) | Fremouw | As received | 4.2 | 22.5 | 62.1 | 11.2 | 3.0 | 67.7 | 1.8 | 15.9 | 0.4 | 11.2 | 10,780 |
| | | Moisture free | | 23.4 | 64.9 | 11.7 | 2.6 | 70.6 | 1.8 | 12.8 | 0.5 | 11.7 | 11,240 |
| | | Moisture & ash free | | 26.5 | 73.5 | | 3.0 | 80.0 | 2.1 | 14.4 | 0.5 | | 12,730 |

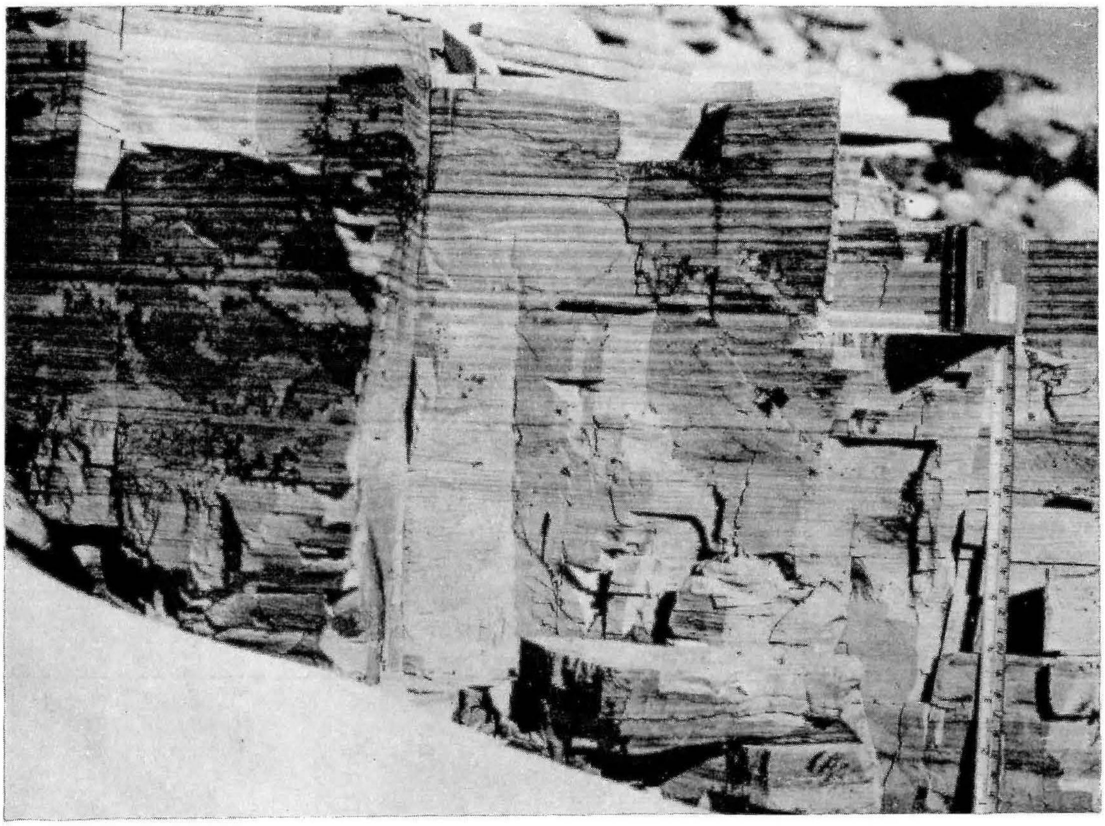


Figure 24. Varvoid lamination 400 m above the base of the Buckley Formation at Mount Picciotto (P1), Queen Elizabeth Range.

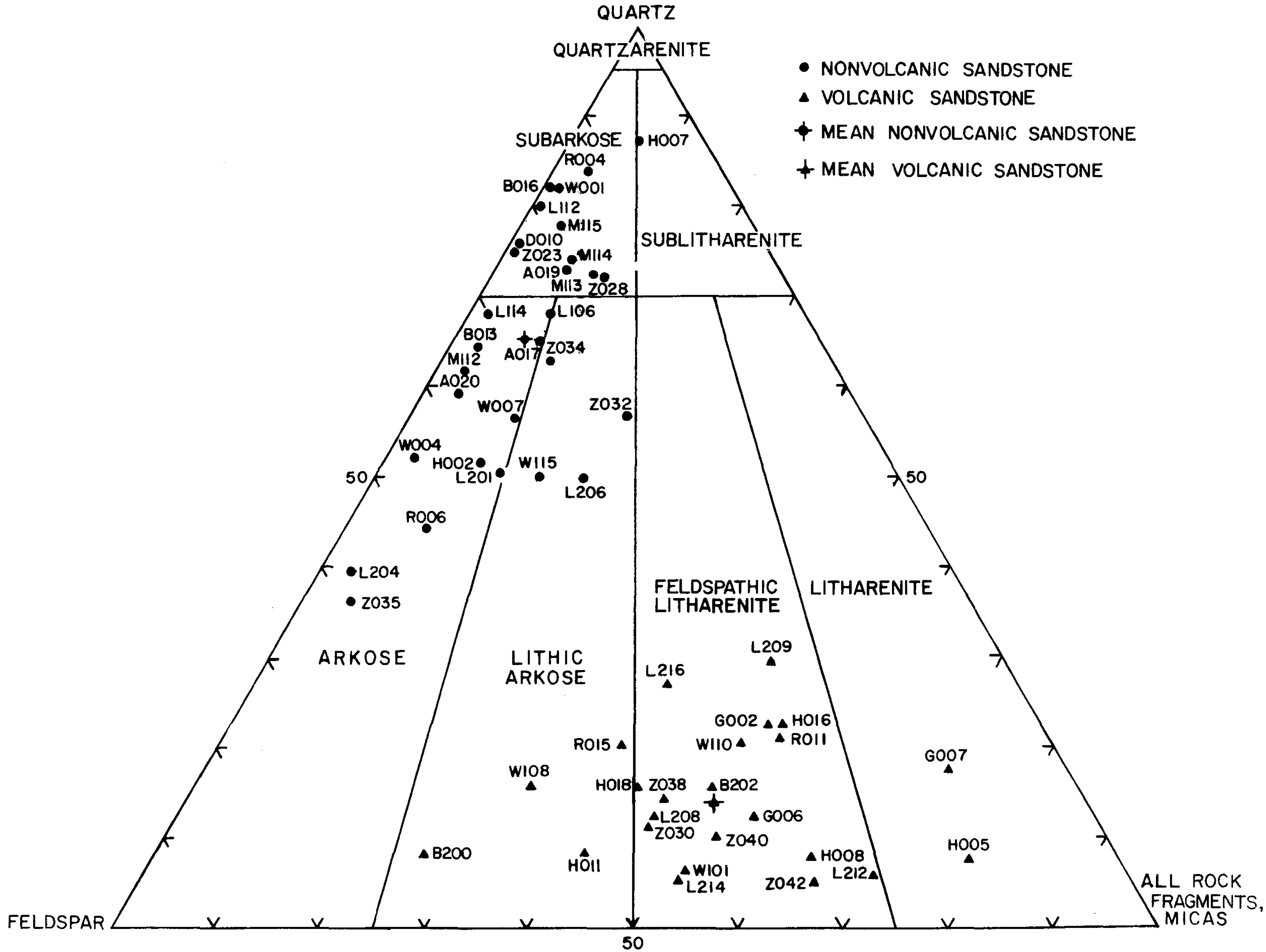



Figure 25. Composition of sandstone samples with less than 20 percent calcite, prehnite or zeolite from the Buckley Formation.

Table 9. Modal analyses (in percent) for samples from the Buckley Formation. Numbers in parentheses are percentages of volcanic fragments. Percentages asterisked (*) in the "Prehnite/Zeolite" column are prehnite

| Sample | Quartz | K-spar | Plag | Lithic | Mica | Calcite | Pr/zeol | Matrix | Rest |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Nonvolcanic sandstone | | | | | |
| H002 | 40 | 0 | 30 | 7 | 0 | 0 | 0 | 19 | 5 |
| H007 | 73 | 0 | 5 | 5 | 0 | 7 | 0 | 10 | 0 |
| B013 | 56 | 7 | 20 | 1 | 2 | 0 | 0 | 13 | 1 |
| B016 | 67 | 4 | 10 | 1 | 0 | 1 | 0 | 17 | 0 |
| W001 | 64 | 0 | 13 | 1 | 0 | 0 | 0 | 22 | 1 |
| W004 | 39 | 1 | 33 | 1 | 1 | 0 | 0 | 20 | 5 |
| W007 | 49 | 0 | 29 | 8 | 1 | 0 | 0 | 9 | 4 |
| W115 | 42 | 1 | 27 | 6 | 7 | 0 | 0 | 13 | 2 |
| M112 | 57 | 5 | 28 | 2 | 1 | 1 | 0 | 4 | 3 |
| M113 | 60 | 0 | 15 | 3 | 5 | 0 | 0 | 16 | 2 |
| M114 | 60 | 0 | 15 | 1 | 4 | 0 | 0 | 14 | 5 |
| M115 | 72 | 0 | 17 | 3 | 1 | 0 | 0 | 5 | 2 |
| Z023 | 68 | 0 | 22 | 0 | 0 | 0 | 0 | 7 | 3 |
| Z028 | 62 | 1 | 13 | 9 | 0 | 0 | 0 | 13 | 1 |
| Z032 | 35 | 0 | 13 | 9 | 4 | 0 | 0 | 37 | 2 |
| Z034 | 49 | 0 | 21 | 3 | 5 | 0 | 0 | 21 | 2 |
| Z035 | 33 | 8 | 46 | 1 | 4 | 0 | 0 | 7 | 2 |
| R004 | 72 | 5 | 6 | 2 | 0 | 9 | 0 | 5 | 0 |
| R006 | 36 | 10 | 29 | 0 | 6 | 2 | 0 | 15 | 2 |
| L106 | 54 | 2 | 17 | 2 | 5 | 0 | 0 | 18 | 3 |
| L112 | 62 | 0 | 15 | 1 | 0 | 0 | 0 | 21 | 2 |
| L114 | 62 | 11 | 17 | 1 | 1 | 0 | 0 | 8 | 1 |
| L201 | 38 | 1 | 28 | 1 | 8 | 0 | 0 | 22 | 3 |
| L204 | 29 | 4 | 37 | 0 | 2 | 3 | 0 | 21 | 4 |
| L206 | 41 | 12 | 14 | 3 | 14 | 5 | 0 | 9 | 4 |
| D010 | 56 | 14 | 2 | 1 | 4 | 4 | 0 | 15 | 4 |
| A017 | 55 | 8 | 15 | 4 | 3 | 1 | 0 | 14 | 1 |
| A019 | 63 | 9 | 10 | 0 | 0 | 12 | 1 | 11 | 3 |
| A020 | 47 | 7 | 22 | 2 | 0 | 0 | 0 | 15 | 5 |
| Mean | 53.1 | 3.8 | 19.6 | 2.7 | 2.7 | | | 14.1 | 2.5 |
| Standard Deviation | 13.0 | 4.4 | 10.0 | 2.8 | 3.2 | | | 7.3 | 1.5 |
| | | | | Volcanic Sandstone | | | | | |
| H005 | 5 | 0 | 9 | 48(48) | 0 | 0 | 0 | 36 | 2 |
| H008 | 5 | 0 | 20 | 43(43) | 0 | 0 | 0 | 26 | 6 |
| H011 | 4 | 0 | 43 | 22(21) | 1 | 5 | 0 | 22 | 2 |
| H016 | 14 | 0 | 16 | 33(33) | 0 | 0 | 4 | 28 | 9 |
| H018 | 9 | 5 | 22 | 27(25) | 0 | 0 | 0 | 32 | 4 |
| G002 | 14 | 1 | 15 | 27(24) | 6 | 0 | 0 | 31 | 7 |
| G006 | 7 | 1 | 18 | 32(32) | 0 | 0 | 0 | 40 | 2 |
| G007 | 13 | 0 | 9 | 53(52) | 0 | 0 | 6 | 18 | 7 |
| B200 | 6 | 0 | 55 | 21(20) | 0 | 0 | 8 | 7 | 11 |
| B202 | 7 | 2 | 16 | 25(22) | 1 | 0 | 0 | 48 | 1 |
| W101 | 5 | 0 | 35 | 45(43) | 0 | 0 | 0 | 7 | 7 |
| W108 | 13 | 0 | 44 | 27(16) | 0 | 0 | 7* | 1 | 14 |
| W110 | 16 | 0 | 23 | 37(33) | 2 | 0 | 0 | 19 | 3 |
| Z030 | 10 | 2 | 35 | 38(36) | 1 | 0 | 0 | 11 | 4 |
| Z038 | 10 | 0 | 29 | 33(30) | 1 | 0 | 0 | 21 | 5 |
| Z040 | 6 | 1 | 24 | 33(30) | 1 | 0 | 0 | 32 | 3 |
| Z042 | 4 | 1 | 23 | 48(47) | 2 | 0 | 1 | 20 | 3 |
| R011 | 13 | 0 | 16 | 30(30) | 2 | 2 | 0 | 35 | 3 |
| R015 | 15 | 3 | 28 | 30(28) | 0 | 1 | 1 | 20 | 2 |
| L208 | 9 | 0 | 31 | 34(31) | 0 | 1 | 0 | 22 | 2 |
| L209 | 22 | 0 | 16 | 33(32) | 2 | 2 | 0 | 23 | 1 |
| L212 | 4 | 0 | 15 | 42(40) | 1 | 0 | 0 | 37 | 1 |
| L214 | 4 | 1 | 36 | 44(43) | 1 | 3 | 0 | 11 | 1 |
| L216 | 17 | 4 | 17 | 24(22) | 0 | 32 | 0 | 6 | 0 |
| Mean | 9.7 | 0.9 | 24.8 | 34.5 | 0.9 | | | 23.1 | 4.2 |
| Standard Deviation | 5.0 | 1.4 | 11.7 | 9.0 | 1.2 | | | 12.0 | 3.5 |
| | | | | Samples with more than 20 percent calcite, prehnite or zeolite | | | | | |
| G013 | 2 | 0 | 2 | 18(18) | 0 | 0 | 61 | 14 | 3 |
| G015 | 11 | 0 | 11 | 20(19) | 0 | 0 | 26 | 29 | 3 |
| E002 | 13 | 0 | 0 | 1(1) | 0 | 0 | 85 | 0 | 1 |
| B014 | 45 | 5 | 20 | 3(1) | 0 | 0 | 23 | 2 | 2 |
| W114 | 15 | 0 | 28 | 17(16) | 0 | 25 | 0 | 7 | 8 |
| Z026 | 0 | 0 | 0 | 0 | 0 | 20 | 58* | 0 | 22 |
| R001 | 60 | 2 | 12 | 1(1) | 0 | 0 | 23 | 1 | 1 |
| R009 | 32 | 11 | 24 | 0 | 2 | 23 | 0 | 5 | 3 |
| L203 | 21 | 7 | 2 | 0 | 0 | 1 | 66* | 0 | 3 |

in most sections, but the lowest level at which volcanic fragments were clearly recognized is at the base of the formation near Mount Wild (B012).

Quartz and feldspar grains in the Buckley Formation are mainly angular to subrounded, whereas volcanic fragments tend to be subrounded to well-rounded. The heavy minerals are more varied than in Fairchild sandstone, and include, as well as garnet, zircon and tourmaline, and a granular epidote-like mineral that may be secondary. Opaque minerals are very common in some of the volcanic sandstones. Mica (both muscovite and light- to dark-brown biotite) tends to be more common in the arkosic and subarkosic ($\bar{x}$ = 2.7 percent) than in the volcanic sandstone samples ($\bar{x}$ = 0.5 percent), though the variation is large. Muscovite normally occurs as large clear flakes, whereas biotite often appears leached and as small wavy flakes clouded with fine black specks.

The arkosic and subarkosic sandstone samples have a slightly lower average quartz content than those of the Fairchild Formation. The K-feldspar, mostly plutonic in origin as shown by the common grid-iron twinning, is almost as common in samples of the Buckley Formation from the Queen Elizabeth and south Queen Alexandra Ranges in the west ($\bar{x}$ = 7 percent) as it is in samples from the Fairchild Formation throughout the area ($\bar{x}$ = 9 percent). However, K-feldspar in samples (Table 9, H002 to Z035, less B013 and B016) from the Buckley Formation in the east averages less than 1 percent, although the total feldspar content ($\bar{x}$ = 24 percent) is not very different from that of the formation to the west ($\bar{x}$ = 20 percent).

These figures indicate that the quartz-plagioclase-K-feldspar source which supplied sand from the northwest quadrant (Fig. 4) to the entire area in Fairchild times was restricted to an area west of the Queen Elizabeth Range in Buckley times. A new and independent quartz-plagioclase source dominated Buckley sedimentation in the east, although occasionally the K-feldspar-rich sand from the west reached as far east as Mount Miller (Z035).

The volcanic sandstone samples are much lower in quartz ($\bar{x}$ = 10 percent) and K-feldspar ($\bar{x}$ = 1 percent) and much higher in plagioclase and lithic fragments ($\bar{x}$ = 25 percent, 35 percent, respectively) than the arkosic and subarkosic sandstone samples (Table 9). Although one to three percent of the rock is made up of grains of sedimentary or metasedimentary origin, most lithic fragments are of the type described in Table 3 under "volcanic fragments." Many of the volcanic fragments, which are altered to varying degrees, appear to have relict vesicular and flow textures (Figs. 5, 6; Barrett, 1969). A few samples (especially B202 and Z040) have a very high percentage of matrix. This is probably due to the difficulty in recognizing some individual volcanic fragments because of secondary alteration. Much of the matrix in these samples is very-fine-grained, dark gray under crossed nicols, and has a poorly developed foliation.

Volcanic material in the Permian Beacon rocks was first recognized by Minshew (1967), though it had been found previously in the Triassic Beacon (Barrett in McGregor, 1965). Minshew found pyroclastic detritus in sandstone beds throughout the Queen Maud Formation in the Scott Glacier area, and noted the dominance of this material in the upper part of the formation. More recently, Gregory (in Adamson and others, in preparation) has recognized relict volcanic textures in thin sections of sandstones high in the Buckley Coal Measures in the Geologists Range at the head of the Nimrod Glacier.

Metamorphism resulting largely from the high temperatures induced by sills has caused the growth of prehnite and, less commonly, grossularite in calcareous beds near sill contacts, and the alternation of some feldspar, rock fragments and matrix to zeolite. Nine sandstone, seven of them volcanic, were examined by X-ray diffractometer (Table 10). Point counts indicated zeolite percentages from 8 to 85 for four sandstones, and for these laumontite peaks were clearly identifiable on the diffractograms. However laumonite peaks were also obtained for two of the five samples that were thought to contain less than one percent zeolite (Z042, L214), suggesting that in these cases zeolitization of the matrix might be widespread. No zeolite other than laumontite was found in these samples. Plagioclase composition in one non-volcanic (L114) and three volcanic sandstones was examined by U-stage. In one sample (H011) only albite was found, but in the other three (Z038, B200, L114) both oligoclase-andesine and low temperature albite are present, indicating that in some cases only partial albitization has taken place.

Prehnite, grossularite and laumontite have been reported previously from the Permian Beacon rocks of the Axel Heiberg-Shackleton Glacier area by Barrett (1966). Prehnite and laumontite also were found in the Scott Glacier-Wisconsin Range area by Minshew (1967), who reported extensive albitization of the Permian volcanic beds and in the Geologists Range by Gregory (in Adamson and others, in preparation).

There seems to be little textural difference between the volcanic and nonvolcanic sandstones of the Buckley Formation (Table 4), which are fine- to medium-grained and moderately sorted. Presumably at least the final stages of transportation and deposition were similar.

### Primary structures

Most of the sandstone units, particularly in the lower part of the formation, contain trough-cross-bedding, with sets from 15 to 60 cm thick. Some sandstone units, however, show only low angle discordant bedding, like that described from the Fairchild Formation. Parting lineation was rarely recorded, probably because of the lack of well-cleaved bedding surfaces.

Table 10. Minerals identified by X-ray diffractometer in samples of Beacon rocks. Relative abundance is estimated from heights of major peaks. x - present, xx - common, xxx - abundant. Modal analyses are available in tables elsewhere in the report for asterisked (*) samples

| Sample | Lithology | Quartz | Feldspar | Laumontite | Clinoptilolite | Mordenite | Stilbite | Analcite | Prehnite | Mica | Chlorite | Unknown |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Fairchild Formation | | | | | | | | | |
| M400 | Arkosic ss | xxx | xxx | | | | | | | xx | xx | |
| | | | Buckley Formation | | | | | | | | | |
| *H011 | Volcanic ss | xxx | xxx | | | | | | | | | |
| *E002 | ? Volcanic ss | xxx | xx | xxx | | | | | | x | x | |
| *B014 | ? Arkosic ss | xxx | x | x | | | | | | | | |
| *B200 | Volcanic ss | xxx | xxx | xx | | | | | | x | | |
| *Z038 | Volcanic ss | xxx | xxx | | | | | | | | x | |
| *Z042 | Volcanic ss | xxx | xxx | xx | | | | | | x | x | |
| *R001 | ? Subarkosic ss | xxx | xxx | xx | | | | | | | x | x |
| P201 | Hornfels | xx | | | | | | | xxx | | | x |
| *L208 | Volcanic ss | xxx | xxx | | | | | | | xx | xx | |
| *L214 | Volcanic ss | xxx | xxx | xx | | | | | | x | x | |
| | | | Fremouw Formation | | | | | | | | | |
| *G015C | Prehnitized quartz ss | xxx | | | | | | | xxx | | | |
| *G022 | Volcanic ss | xxx | xxx | xx | | | | | | | x | |
| *G028 | Volcanic ss | xxx | xxx | xx | | | | | | | | |
| G038 | Radiating crystals in green gray mudstone | | | | | | xxx | | | | | |
| *G207 | Volcanic ss | xxx | xxx | xx | | | | | | | | |
| *E022 | Volcanic ss | xxx | xxx | xx | | | | | | | x | |
| *E026 | Volcanic ss | xxx | xxx | xx | | | | | | x | x | |
| *E028 | Volcanic ss | xxx | xxx | | | | | | | x | x | |
| *F014 | Volcanic ss | xxx | xxx | xx | | | | | | x | xx | |
| *F020 | Volcanic ss | xxx | xx | xx | | | | | | x | x | |
| *F024 | Volcanic ss | xxx | xxx | xx | | | | | | x | x | |
| F028 | ? Tuff | xxx | xx | | | | | | | x | x | |
| *F034 | Volcanic ss | xxx | xxx | xx | | | | | | x | x | |
| *F056 | Volcanic ss | xxx | xxx | | | | | | | x | x | |
| | | | Falla Formation | | | | | | | | | |
| *G208 | Volcanic ss | xxx | xx | | | | xxx | | | | | x |
| K020 | Tuff | xxx | xxx | | | x | | | | | | |
| K023 | Tuff | xxx | x | | | x | | | | | | |
| *K025 | Volcanic ss | xxx | xxx | | xxx | | | | | | | |
| F220 | Tuff | xxx | xx | | | | | | | x | | |
| F226 | Mainly pink mineral from joints and small cavities | xxx | xx | | | | | xxx | | | | |
| F228 | Tuff | xxx | x | | | | | x | | | | |
| F239 | Tuff | xxx | xx | | | | | xxx | | | | x |
| F247 | Tuff | xxx | xxx | | xx | | | | | | | x |
| F249 | Tuff | xxx | xx | | | | | | | | | x |
| | | | Prebble Formation | | | | | | | | | |
| 0001 | Paraconglomerate | xx | xx | | xxx | | | | | | | |
| 0008 | ? Silicified tuff | xxx | | | | | | | | | | |
| F255 | Paraconglomerate | xx | xx | | xx | | | xx | | | | |
| K030 | Paraconglomerate | xxx | xxx | | xx | | | | | | | |
| K031 | Paraconglomerate | xxx | xx | | xx | | | | | | | |

Microcrosslamination is common in the very-fine-grained sandstone and shale units into which the coarser grained sandstone normally grades. Well-preserved ripple marks are quite rare, and were found only in the lower 300 m of the formation. They normally have a low symmetrical sinusoidal cross-section, but have an asymmetrical internal structure of dipping laminations from which the flow direction can be determined. Twelve sets of ripple marks were measured about 137 m above the base of the formation on Mount Picciotto (P1). The wavelength averaged about 8 cm and the ripple index about 18. Ripple marks measured from other sections have wavelengths from 3 to 10 cm and ripple indices from 5 to 16.

### Paleontology

Plant fossils, mainly leaves of Glossopteris and associated genera, are common particularly in the middle and upper parts of the formation. A number of collections were made and are presently being studied by Dr. J. M. Schopf. Concentrations of flattened stems and logs, some silicified and some volatilized by diabase intrusion, were found in volcanic sandstones. All the silicified logs have well-developed growth rings, indicating a strongly seasonal climate. Small roots found in place 100 m below the top of the formation at Graphite Peak and 210 m below the top of the formation at McIntyre Promontory have been identified by Dr. Schopf as Vertebraria.

Trails and burrows, although not common, were found at all levels in the formation, and in most of the sections measured. The trails, normally about 2 mm wide, are slightly sinuous, with some more than 30 cm long. At four localities (M4, P1, L2, A4) burrows from 3 to 5 mm wide are associated with trails (Fig. 26). Ovoid structures (possibly coprolites) were found with the trails at L2 and Z0.

### Correlation and age

Beds equivalent to the Buckley Formation have been reported from most parts of the Transantarctic Mountains. In south Victoria Land many writers -- among them Ferrar (1907), Webb and McKelvey (1959), Allen (1962), Gunn and Warren (1962), and Matz and Hayes (1966) -- have described Glossopteris-bearing coal measures that are now known to disconformably overlie Devonian quartzarenite (Mirsky, 1965; Harrington, 1965; Matz, 1968). In the Darwin Mountains, 450 km north of the Beardmore Glacier, the equivalent of the Buckley Formation is the 93-m-thick Misthound Coal Measures (Haskell and others, 1965), which contains Gangamopteris, and which disconformably overlies the Darwin Tillite.

Laird and others (in preparation) extended the name Buckley Coal Measures into the Nimrod Glacier area. The lower part of the formation in that area has been compared with the Fairchild Formation (p. 31), and although no quartz pebble horizon was reported, the upper part of their Buckley Coal Measures is here considered equivalent to

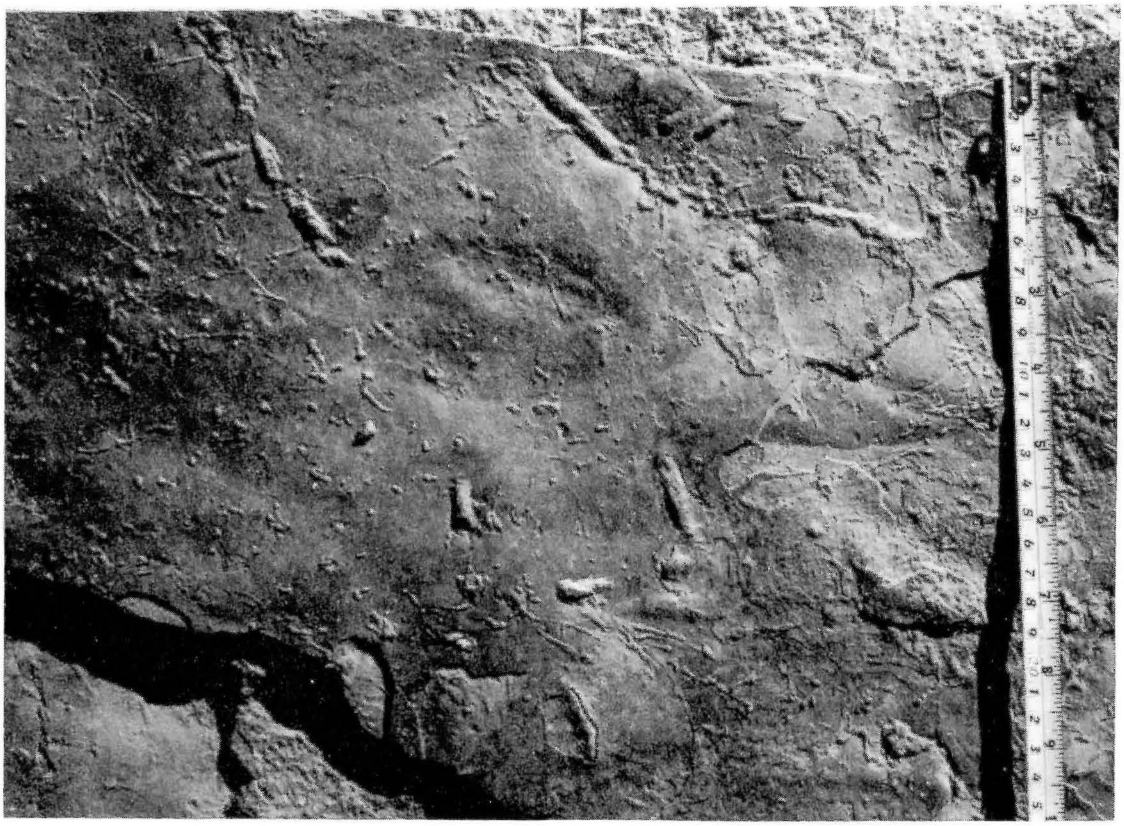


Figure 26. Trails, burrows and coprolites (?) 160 m above the base of the Buckley Formation at Mount Picciotto (P1), Queen Elizabeth Range.

the Buckley Formation. Young and Ryburn (1968) also did not report a quartz pebble horizon in the Buckley Coal Measures of Buckley Island, although in Shackleton (1909), the lower part of a 460-m-thick section of coal measures is described as "Seven-hundred-foot [210 m] sandstone with numerous water worn quartz pebbles in the lower beds. These pebbles are from one to two inches in diameter." Young and Ryburn do describe, as the Lower Buckley Coal Measures, a 222-m-thick predominantly sandstone unit of massive appearance, which is here considered equivalent to the

Fairchild Formation. The Middle Buckley Coal Measures, which are described as "carbonaceous and micaceous mudstone, siltstone and cross-bedded quartz sandstone" by Young and Ryburn (1968), are considered equivalent to the Buckley Formation.

Units that are equivalent to the Buckley Formation in the Shackleton Glacier area to the south are called the Buckley Coal Measures by Wade and others (1965); in the central Queen Maud Mountains they were referred to as unit C by Barrett (1965). Minshew (in Doumani and Minshew, 1965) called equivalent beds the Queen Maud Formation in the area from the Amundsen Glacier to the Wisconsin Range. They are represented, in the Ohio Range, by the middle and upper parts of the Mount Glossopteris Formation (Long, 1965).

The assignment of a Permian age to the Buckley Formation depends largely on the age of suggested equivalent units in south Victoria Land and the Ohio Range, where floral assemblages and other fossils have been studied in more detail. Plumstead (1962) concluded that assemblages that included *Gangamopteris* indicate a "Permo-Carboniferous" age, whereas the higher pure *Glossopteris* collections are of Permian age. However, a lower limit for the *Glossopteris*-bearing coal measures of the central Transantarctic Mountains has been established through the discovery of spores with Permian affinities in the Buckeye Tillite of the Ohio Range (p. 34, Schopf, unpublished manuscript, 1966). That the upper part of the formation is no younger than Permian is suggested by the presence of *Glossopteris* without *Dicroidium* 150 m below the top of the formation at the head of the Wahl Glacier (Wl), and 4 m below the top of the formation at Graphite Peak (GO). Also, Doumani and Tasch (1965) have reported conchostracans of Middle and Upper Permian age from the upper part of the Mount Glossopteris Formation, which is the youngest unit in the Ohio Range.

### Environment of deposition and source

The trough-cross-bedded sandstone, the shale fragments, the coal, logs and leaves, and the "fining-upwards" cycles of the Buckley Formation indicate deposition on a slowly subsiding flood plain with ephemeral lakes and swamps and meandering streams that flowed generally to the east and south (Fig. 4).

The possibility of a glacial origin for the varvoid mudstone in the Buckley Formation was seriously considered by Grindley (1963), but neither the mudstone nor the adjacent beds have features other than the graded laminae to associate them with glacial activity. It is possible that the grading resulted from deposition in shallow lakes in a strongly seasonal climate. Such a climate is independently indicated by the well-developed growth rings in silicified logs from the Buckley Formation.

The mineralogy indicates two different source areas for the nonvolcanic sand of the Buckley Formation. An area of granitic and metasedimentary rocks, like that which provided sand for the Mackellar and Fairchild Formations, supplied sediment to the Queen Elizabeth and southern Queen Alexandra Ranges from the west according to paleocurrent data (Barrett, in preparation, a). The eastern part of the Beardmore Glacier area was supplied from the north by a new quartz-plagioclase source, indicating an area with much less granite exposed than that which supplied the underlying formations. Because lithologic equivalents of the Buckley Formation extend much farther north than those of the Mackellar and Fairchild Formations, the quartz-plagioclase source for the eastern part of the area probably also lay farther north than the quartz-plagioclase-k-feldspar source that supplied the Mackellar the Fairchild and some of the Buckley Formation.

Intermediate-acid volcanism began shortly after the deposition of the lowest beds in the formation, and quickly became the dominant, though a discontinuous, source for sand detritus. The sand includes both redeposited pyroclastic and flow fragments, but no vents or flows of Permian age have been found in the Transantarctic Mountains.

## Triassic System

### Fremouw Formation

#### Definition

The name Fremouw Formation is here proposed for quartzose (mainly subarkosic) sandstone and interbedded noncarbonaceous mudstone beds totaling 75 to 125 m thick, and the overlying 530 m or more of greenish-gray and gray mudstone and light-colored sandstone, that lie disconformably on the Buckley Formation in the Beardmore Glacier area. The type section (FO, Fig. 27) is on the southern slopes of a group of low peaks on the south side of the mouth of the Prebble Glacier, and extends upward from the top of a dolerite sill at ice level (84° 17.8' S; 164° 18' E) about 30 m below and 300 m southwest of Fremouw Peak, from which the formation name was taken.

#### Distribution and thickness

In the Queen Alexandra Range, the Fremouw Formation extends from the Marshall Mountains in the south to the Wahl Glacier in the north. Further north a massive sandstone at least 200 m thick can be traced by eye, as Grindley (1963) noted, around the east, north and west margin of the Grindley Plateau, and might be equivalent to the basal quartzose sandstone beds near the head of the Wahl Glacier. The boulders of medium- to coarse-grained subarkose 745 m stratigraphically above the base of the Buckley Formation near the head of the Lowery Glacier (L1, L2) may also come from this horizon.

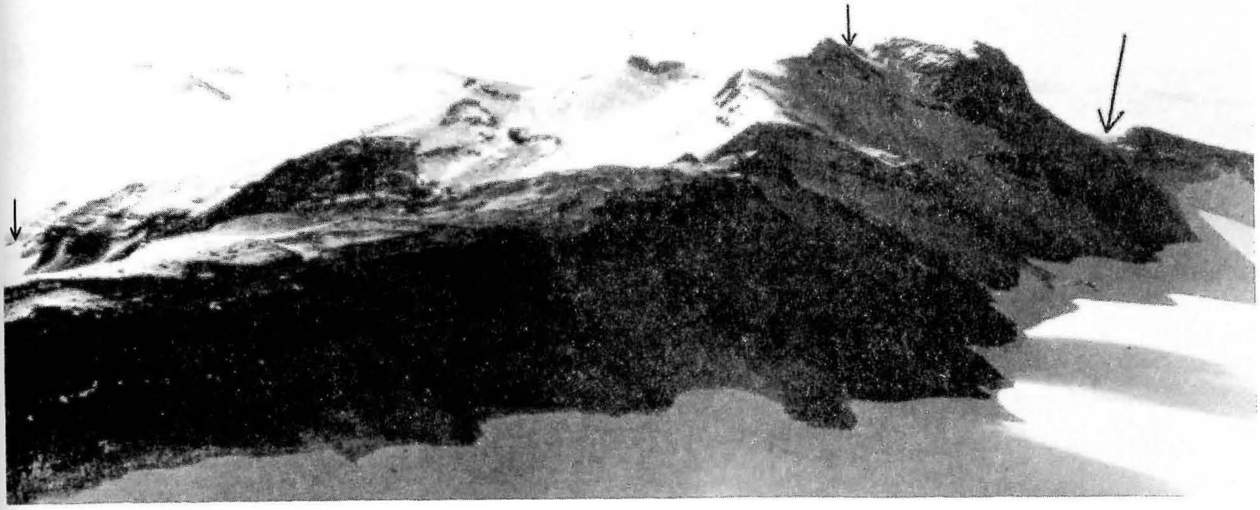


Figure 27. Looking northwest from F3 to Fremouw Peak, central Queen Alexandra Range. Short arrows indicate the base of the type section of the Fremouw Formation (FO), and the upper contact with the Falla Formation. The long arrow indicates the col in which large logs were found.

Figure 28. Looking up 1000 m from near the base of EO to the summit of Mount Kinsey. Foreground slopes are carbonaceous shale and mudstone of the Buckley Formation. The arrow indicates the base of the bluff-forming quartzose sandstone beds that dominate the lower part of the Fremouw Formation.

The Fremouw Formation extends at least as far west as Mount Sirius, where a total of 190 m from the lower and middle parts of the formation were measured. The sedimentary strata of the MacAlpine Hills, from 15 to 40 km north, appear from a distance to be of similar lithology and in the same stratigraphic position.

The Fremouw Formation is extensively exposed east of the Beardmore Glacier from the Supporters Range to McIntyre Promontory, 100 km to the east. Near Graphite Peak a composite section, which includes both formational boundaries but in which the correlation from GO and G1 is poor, is at least 670 m thick, and perhaps as much as 800 m.

The greatest thickness measured west of the Beardmore Glacier is 614 m at the type section (FO). That may be close to the total thickness for the formation in this area, for a thin medium- to coarse-grained quartzose sandstone interval begins 294 m above the base of the type section, and at W1 on the Wahl Glacier, where the lower contact of the formation is exposed, a similar quartzose sandstone was found 297 m above the base of the formation. At Mount Kinsey the quartzose beds begin 350 m above the base of the formation, but at Graphite Peak, 120 km southeast of the Wahl Glacier, they crop out only 295 m above the base of the formation.

Lower contact

At the head of the Wahl Glacier (W1) the lowest quartzose sandstone bed rests disconformably on carbonaceous shale of the Buckley Formation. Mudstone interbedded with the quartzose sandstone is light greenish gray and noncarbonaceous, in contrast to the shale of the upper part of the Buckley Formation. The lower contact of the Fremouw Formation here has no detectable relief over several hundred meters, but there are shale fragments as much as 15 cm across in the lower meter of the basal quartzose sandstone.

The lower contact east of the Beardmore Glacier was seen at Mount Kinsey (EO), Graphite Peak (GO), and McIntyre Promontory (HO). At Mount Kinsey the change across the contact from carbonaceous *Glossopteris*-bearing mudstone and coal to bluff-forming quartzose sandstone and light-greenish-gray siltstone is striking (Fig. 28). The base of the lowest quartzose sandstone, which overlies a thin coal bed, is sharp but not demonstrably erosional, although most of the sandstone beds in the overlying 70 m provide evidence of local erosion in the form of mudstone fragments near the base.

The distinction between the Buckley and Fremouw Formations at Graphite Peak and McIntyre Promontory is clear, but the precise location of the boundary is not. The boundary in both places was located in the field primarily on the basis of the sudden disappearance of carbonaceous material, and was placed at the overlying disconformity.

Petrographic examination showed that in the Buckley Formation of Graphite Peak, a sample (GO15B) from the top of the uppermost unit, 4 m of very-light-gray fine-grained sandstone, is several times more quartzose and less feldspatic than other Buckley sandstone in the section, but is very like the overlying lower Fremouw sandstones (see Table 13, p. 57, Fig. 31), with which it has been included. The lower contact of the 4-m-thick unit appears gradational into Glossopteris-bearing dark shale of the Buckley Formation. McGregor (1965), who first described the Graphite Peak section, placed the upper boundary of the Buckley Formation at the base of a prominent quartzose sandstone 62 m higher in the section, probably because it is coarser grained, pebbly, and more obviously quartzose than in sandstone beds beneath.

At McIntyre Promontory, just above a dolerite sill half way up the section, a coal seam 2.4 m thick with an iron-stained upper surface is overlain by a "fining-upwards" cycle 60 m thick of sandstone and noncarbonaceous siltstone. The sandstone is very similar to many in the upper Buckley Formation -- it is fine-grained, contains some silicified woody streaks in the upper part and contains much volcanic detritus (HO18, Table 9) -- but the siltstone is like those of the overlying Fremouw Formation. Both units of the overlying sandstone-siltstone cycle are typical of the lower Fremouw Formation -- the sandstone is subarkosic (HO19, Table 11) with abundant well-rounded quartz grains. The base of the Fremouw Formation is tentatively placed at the erosion surface marking the base of the latter cycle.

Lithology

The lower and middle parts of the Fremouw Formation consists of an alternating sequence of sandstone and greenish-gray siltstone lacking in carbonaceous material. In the upper part of the formation sandstone dominates the section and carbonaceous material becomes common. The sandstone is mostly lithic arkose and feldspathic litharenite but in the lower 75 to 125 m and in a thin interval in the middle of the formation the sandstone is subarkosic. Cycles are best developed in the lower beds and consist of, in ascending order, an erosion surface, a massive trough-cross-bedded sandstone with siltstone fragments near the base, and a small-scale cross-bedded fine-grained sandstone that grades upward into light-greenish-gray siltstone.

The basal beds were first found on the Wahl Glacier, where they comprise 6 cycles from 8 to 41 m thick, in which each erosion surface is overlain by a massive white medium-grained cross-bedded quartzose sandstone that weathers reddish brown. Scattered small quartz pebbles are present in the lower meter or two of each cycle, but mudstone fragments were found near the base and at higher levels in the cycle. The upper part of each cycle consists of very-fine-grained light-greenish-gray sandstone which in some instances is followed by light-greenish-gray shaly siltstone. These well-developed cycles at W1 pass upward into an alternating sequence about 300 m thick of light-greenish-gray mudstone and sandstone.

At the type section (FO) of the Fremouw Formation, the lower 79 m, which overlies a diabase sill, have a cyclic character similar to that of the basal quartzose beds at W1 and elsewhere and are probably equivalent, though the beds at FO are a little less quartzose than most others at that stratigraphic position.

From 79 to 246 m above the base of the type section the formation consists of greenish-gray mudstone and very-fine-grained sandstone, with occasional lenses of light-gray or light-pink fine- to medium-grained sandstone, as much as three meters thick, resting on erosion surfaces. Just above these beds there is a medium-grained sandstone unit with stringers of subrounded to well-rounded pebbles, as much as 12 cm across, of acid to intermediate volcanic rocks, vein quartz, and metasedimentary rocks (p. 74).

The interval of quartzose sandstone in the middle of the formation at FO, from 294 to 324 m above the base of the section, includes two beds of medium- to coarse-grained white quartzose sandstone 18 and 8 m thick. Both beds have concentrates of red garnet in the lower meter or two, and are slightly calcareous. Similar but thinner pebbly medium- to coarse- grained quartzose sandstone units were found from 39 to 62 m above the base of F1 and in the lower 17 m of F3, both on the nearby Pebble Glacier. The quartzose interval was also found southeast of the Beardmore Glacier (p. 50).

The upper part of the formation at the type section consists mostly of light-gray slope-forming fine- to medium-grained sandstone about 300 m thick. Accumulations of mudstone and fine-grained sandstone fragments, mostly from 2 to 10 cm but as much as 50 cm across, are common just above erosion surfaces at the base of and within this sandstone. Coal streaks and fragments of stems and logs as much as 1 m across were also found.

This level at which carbonaceous material becomes abundant in the upper part of the Fremouw Formation varies considerably even within the Prebble Glacier area. Only the upper 30 m has much carbonaceous material at the type section, but at F3, 4.8 km to the southeast, the upper 120 m is carbonaceous. About 3.2 km farther to the southeast, at F5, carbonaceous shale first appears 265 m below the top of the formation, but at Mount Kirkpatrick and at Kenyon Peaks the uppermost Fremouw Formation contains no carbonaceous shale. Coal beds were found at two localities in the type area. A 2.4 m-thick bed, 9 m below the top of the formation at Fremouw Peak (FO), has been partly coked by the adjacent dolerite sill. At F3 there are two coal beds, 1.5 and 3 m thick, in the upper 19 m of the formation (Fig. 29).

Figure 30, which shows the proportion of fine-to medium-grained sandstone in each part of the formation, gives some basis for three broad divisions of the formation, that is, into subarkosic sandstone, greenish-gray mudstone, and volcanic sandstone. These divisions

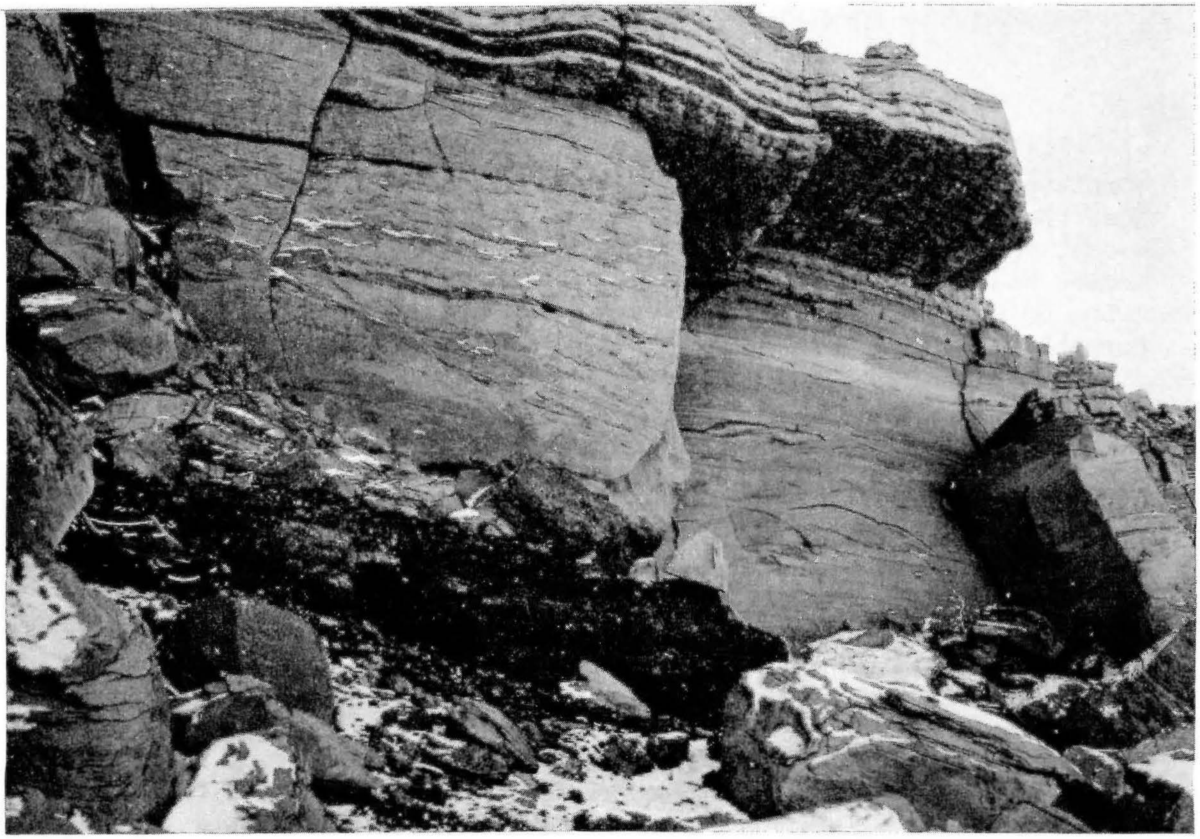


Figure 29. A coal bed 1.5 m thick in the upper few meters of the Fremouw Formation at F3, Prebble Glacier. The lowest sandstone of the Falla Formation is in the upper part of the photograph.

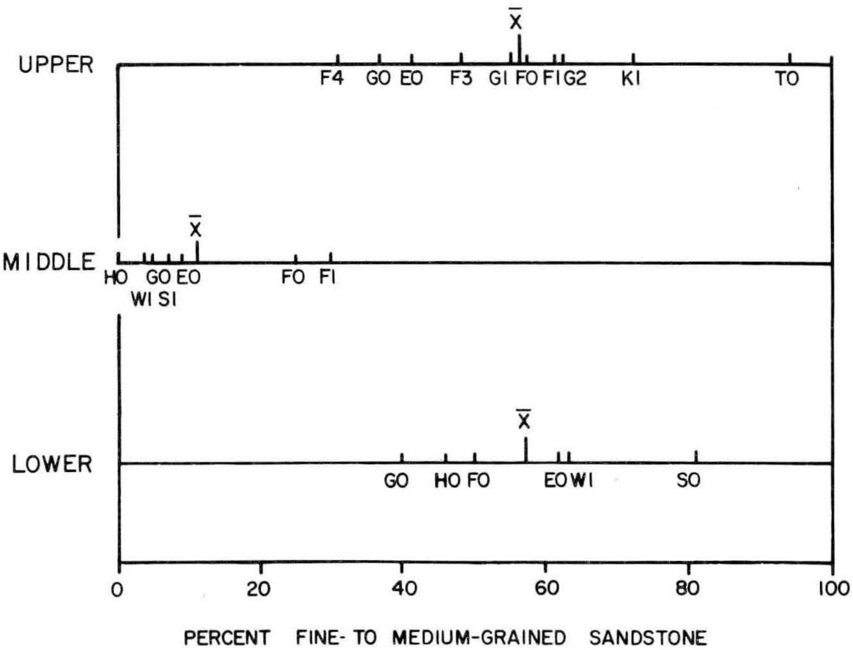



Figure 30. The thickness of fine- to medium-grained sandstone in each section measured in the Fremouw Formation is plotted as a percentage of the total thickness of that section. $\overline{X}$ - arithmetic mean.

are readily apparent in the only other area containing a more or less complete section, the area near Graphite Peak, 120 km to the southwest. Here the upper part of the section also becomes very carbonaceous and has a coal bed, 3 m thick, 60 m below the upper contact; silicified coaly lenses and logs with well-preserved growth rings, a feature of the upper 100 m of the type section, are common here in the upper 200 m of the formation.

Phosphate pebbles

Three localities as much as 180 km apart (HO, GO, SO) have a bed about 15 m thick of medium-grained subarkosic sandstone near the top of the quartzose lower part of the Fremouw Formation. This bed contains conspicuous floating rounded pebbles of white quartz and dark-gray spheroidal pebbles and cobbles of phosphate. Most phosphatic clasts are from 1 to 4 cm across, and have a rough surface that readily absorbs moisture. Some have an indistinct foliation. The pebbles are seen in thin section to contain scattered quartz, and less commonly feldspar, grains as much as 0.13 mm long, and thin sericite flakes, all set in a light-brown dense microcrystalline matrix that comprises about 95 percent of the rock. The X-ray powder data (Table 11) for pebbles from Mount Sirius (SO) and Graphite Peak (GO) compare very closely with powder data for fluorapatite. The limited data also indicate that there are no significant mineralogical differences between the three pebbles of the Fremouw Formation even though two came from a locality 125 km away from the third.

Table 11. X-ray powder data for phosphorite pebbles from near the base of the Fremouw Formation. Data from fluorapatite, (McConnell, 1938) are included for comparison. The Fremouw data were obtained from smear mounts and the intensities were calculated from peak heights.

| GO19-A | | GO19-B This report | | SO05 | | Fluorapatite McConnell (1938) | |
|---|---|---|---|---|---|---|---|
| 3 | 3.43 | 3 | 3.45 | 3 | 3.43 | 2 | 3.43 |
| 3 | 3.06 | 2 | 3.06 | 2 | 3.08 | 3 | 3.06 |
| 10 | 2.80 | 10 | 2.80 | 10 | 2.80 | 10 | 2.80 |
| 6 | 2.77+ | 5 | 2.77+ | 5 | 2.77+ | 4 | 2.77 |
| 7 | 2.70 | 9 | 2.71 | 6 | 2.70 | 6 | 2.70 |
| 2 | 2.62 | 2 | 2.62 | 2 | 2.62 | 3 | 2.62 |
| 1 | 2.51 | 1 | 2.51 | 1 | 2.52 | 0.5 | 2.52 |

+shoulder on peak at 2.80 Å

Table 12. Chemical analysis of a phosphate pebble (G019C) from the lower part of the Fremouw Formation at Graphite Peak. In the second column the analysis is recalculated without the oxides marked by an asterisk (*). Also the molecular equivalent of the sulfate has been subtracted from the lime. An analysis of fluorapatite (McConnell, 1938) is included for comparison. Analyst: McCreath.

| | G015C | | Fluorapatite (McConnell, 1938) |
|---|---|---|---|
| | Complete | Recalculated | |
| *$SiO_2$ | 23.46 | | |
| *$TiO_2$ | 0.40 | | |
| *$Al_2O_3$ | 6.01 | | 0.24 |
| *$Fe2O_3$ | 0.09 | | 0.63 |
| *FeO | 2.01 | | |
| MnO | 0.15 | 0.22 | 0.12 |
| MgO | 0.53 | 0.78 | |
| CaO | 34.24 | 50.26 | 55.16 |
| $Na_2O$ | 0.86 | 1.27 | |
| $K_2O$ | 0.78 | 1.15 | |
| $H_2O+$ | 1.86 | 2.75 | 0.01 |
| $P_2O_5$ | 26.56 | 39.30 | 41.30 |
| $CO_2$ | 0.45 | 0.67 | 0.50 |
| *$SO_3$ | 0.48 | | |
| *Cl | $< 0.1$ | | 0.09 |
| F | 2.43 | 3.60 | 3.67 |
| *SrO | $< 0.01$ | | |
| Others | | | 0.42 |
| | 100.42 | 100.00 | 100.58 |

The chemical analysis (Table 12) shows that the pebble does consist mainly of a fluorophosphate mineral, though the silica and alumina percentages indicate that the material is quite impure.

Similar black pebbles and cobbles occur in the basal part of the Dover Sandstone, a quartzose sandstone unit of Devonian age (Schmidt and others, 1965) in the Neptune Range of the Pensacola Mountains (Fig. 1). Beds of phosphate occur in the underlying silty sandstone formation, the Elbow Formation. Their phosphatic character has been established by X-ray analysis (J. B. Cathcart, U. S. Geological Survey, Denver, written communication). Whereas the phosphate in the basal Dover Sandstone is of transported and replacement origin, the phosphate in the underlying Elbow Formation is probably primary sedimentary phosphate.

The dark color, lack of structure other than indistinct foliation, and the fine-grained nature of the Fremouw pebbles suggests that they were derived originally from a marine phosphate deposit (Pettijohn, 1957, p. 475-476). The source of the Fremouw phosphate pebbles is probably from the direction of the Pensacola Mountains, which lie in the up-paleoslope direction (Fig. 4). The immediate source may have been the Dover Sandstone or a lithologic equivalent, or the underlying Elbow Formation or lithologically similar formations between the Beardmore and Pensacola areas.

Petrography

Sandstone in the lower part of the formation is mainly subarkose (Table 13, Fig. 31). Most of the quartz is clear, unstrained, and ranges from subrounded to very-well-rounded. An opaque dust forms from the boundary between quartz grains and the quartz cement. Feldspar is variable in both abundance and composition. Plagioclase is common (ranges from 0 to 21 percent) in samples from the Prebble Glacier (FO), and in Graphite Peak (GO), HO19 (McIntyre Promontory). K-feldspar much of it microcline, comprises from 0 to 13 percent of the rock but averaged only 5 percent. Mica is rare or absent from samples from the lower part of the formation, and volcanic fragments were identified only in samples from the type section, Mount Sirius and McIntyre Promontory. Calcite was found only in FO11 (18 percent), but may have originally been common in prehnite-bearing samples EOO4 from Mount Kinsey and GO15C from Graphite Peak.

The composition of the sandstone from the middle and upper parts of the type section of the formation varies little, apart from the thin quartzose interval. However, samples from Mount Kirkpatrick and Graphite Peak have a higher proportion of rock fragments. Generally, the quartz content ($\bar{x}$ = 22 percent) is considerably lower than that of the nonvolcanic sandstones of the Buckley Formation, and is much higher than that of the Buckley Formation, and is much higher than that of the volcanic sandstones. Plagioclase, which normally is cloudy and in many cases partly zeolitized, is as common as quartz, and K-feldspar is more widespread, though perhaps not as abundant locally, than it is in the Buckley Formation. K-feldspar forms less than one percent of the total rock in only one fifth of the samples from the middle and upper Fremouw

Table 13. Modal analyses (in percent) for samples from the Fremouw Formation. Numbers in parentheses are percentages of volcanic fragments. Percentages asterisked (*) in the "Prehnite/Zeolite" column are prehnite.

| Sample | Quartz | K-Spar | Plag | Lithic | Mica | Calcite | Pr/Zeol | Matrix | Rest |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Lower Fremouw Fm | | | | | |
| H019 | 54 | 0 | 14 | 6 (4) | 0 | 0 | 0 | 22 | 3 |
| H021 | 84 | 9 | 5 | 2 (0) | 0 | 0 | 0 | 0 | 0 |
| G015B | 49 | 0 | 3 | 13 (5) | 1 | 0 | 1 | 31 | 3 |
| G018 | 82 | 1 | 10 | 3 (2) | 0 | 0 | 2 | 2 | 3 |
| E007 | 68 | 4 | 10 | 7 (3) | 0 | 0 | 1 | 8 | 2 |
| F001 | 56 | 5 | 18 | 5 (3) | 0 | 0 | 0 | 14 | 3 |
| F009 | 59 | 8 | 12 | 9 (9) | 0 | 0 | 0 | 9 | 2 |
| F011 | 51 | 0 | 13 | 10 (4) | 0 | 19 | 0 | 5 | 2 |
| S000 | 39 | 3 | 21 | 17 (15) | 0 | 0 | 0 | 18 | 2 |
| S004 | 82 | 4 | 2 | 1 (0) | 0 | 0 | 0 | 9 | 2 |
| W116 | 67 | 9 | 0 | 12 (0) | 0 | 0 | 0 | 11 | 1 |
| W117 | 93 | 4 | 0 | 1 (0) | 0 | 0 | 0 | 2 | 0 |
| W119 | 92 | 2 | 4 | 1 (0) | 0 | 0 | 0 | 1 | 0 |
| W120 | 92 | 6 | 0 | 1 (0) | 0 | 0 | 0 | 1 | 0 |
| W123 | 78 | 4 | 1 | 10 (6) | 0 | 0 | 0 | 5 | 3 |
| L218 | 62 | 13 | 1 | 0 (0) | 0 | 0 | 0 | 22 | 1 |
| Mean | 69.3 | 4.4 | 7.2 | 6.2 | 0.1 | | | 10.0 | 1.7 |
| Standard Deviation | 17.2 | 3.7 | 6.9 | 5.1 | 0.2 | | | 9.2 | 1.1 |
| | | | | Middle and Upper Fremouw Fm | | | | | |
| G022 | 39 | 1 | 12 | 14 (11) | 3 | 0 | 16 | 12 | 19 |
| G025 | 29 | 4 | 15 | 14 (13) | 4 | 0 | 13 | 18 | 16 |
| G028 | 25 | 4 | 14 | 35 (32) | 0 | 0 | 8 | 11 | 11 |
| G106 | 15 | 5 | 12 | 33 (33) | 3 | 0 | 18 | 11 | 20 |
| G201 | 17 | 2 | 18 | 26 (22) | 3 | 0 | 10 | 21 | 13 |
| G207 | 21 | 2 | 19 | 38 (34) | 3 | 0 | 7 | 7 | 10 |
| E009 | 29 | 0 | 24 | 12 (8) | 3 | 0 | 10 | 19 | 13 |
| E028 | 14 | 0 | 27 | 32 (31) | 1 | 0 | 5 | 18 | 7 |
| F014 | 30 | 5 | 25 | 8 (5) | 3 | 0 | 7 | 17 | 12 |
| F020 | 42 | 0 | 12 | 17 (12) | 0 | 1 | 11 | 16 | 12 |
| F022 | 44 | 0 | 11 | 12 (8) | 0 | 0 | 0 | 32 | 2 |
| F024 | 29 | 3 | 15 | 29 (26) | 0 | 1 | 14 | 7 | 15 |
| F026 | 26 | 2 | 26 | 25 (21) | 1 | 0 | 14 | 5 | 16 |
| F029 | 19 | 4 | 28 | 24 (21) | 1 | 0 | 0 | 22 | 1 |
| F034 | 23 | 4 | 24 | 25 (21) | 1 | 0 | 18 | 5 | 19 |
| F044 | 17 | 3 | 30 | 27 (24) | 1 | 0 | 13 | 7 | 15 |
| F045 | 16 | 1 | 23 | 40 (37) | 1 | 1 | 15 | 3 | 15 |
| F050 | 26 | 7 | 22 | 26 (20) | 0 | 0 | 0 | 14 | 4 |
| F053 | 17 | 3 | 30 | 34 (26) | 2 | 2 | 0 | 10 | 2 |
| F056 | 19 | 3 | 29 | 34 (29) | 0 | 3 | 0 | 9 | 3 |
| F502 | 22 | 5 | 25 | 20 (19) | 0 | 2 | 16 | 8 | 18 |
| F504 | 23 | 0 | 17 | 22 (21) | 2 | 0 | 4 | 27 | 8 |
| F509 | 13 | 4 | 19 | 28 (25) | 2 | 1 | 10 | 18 | 15 |
| F514 | 12 | 2 | 15 | 31 (26) | 2 | 2 | 4 | 31 | 6 |
| F529 | 14 | 4 | 21 | 21 (19) | 0 | 0 | 17 | 16 | 24 |
| F533 | 22 | 4 | 19 | 25 (21) | 1 | 5 | 5 | 15 | 9 |
| F534 | 24 | 4 | 11 | 34 (31) | 1 | 1 | 4 | 19 | 6 |
| F535 | 25 | 3 | 22 | 23 (17) | 2 | 1 | 3 | 17 | 6 |
| F537 | 42 | 12 | 9 | 26 (21) | 2 | 0 | 0 | 6 | 3 |
| F538 | 30 | 5 | 19 | 19 (14) | 2 | 1 | 3 | 18 | 6 |
| F540 | 19 | 5 | 21 | 27 (22) | 1 | 2 | 2 | 18 | 7 |
| K101 | 27 | 3 | 16 | 26 (21) | 2 | 0 | 2 | 21 | 5 |
| K103 | 38 | 4 | 7 | 18 (15) | 0 | 0 | 2 | 30 | 4 |
| S105 | 36 | 0 | 20 | 21 (19) | 1 | 1 | 4 | 15 | 6 |
| S110 | 17 | 6 | 29 | 32 (30) | 1 | 0 | 0 | 13 | 2 |
| W130 | 7 | 0 | 16 | 8 (7) | 2 | 10 | 0 | 55 | 2 |
| W132 | 20 | 6 | 25 | 24 (21) | 2 | 4 | 0 | 14 | 5 |
| Mean | 24.0 | 3.3 | 19.6 | 24.6 | 1.4 | | | 16.4 | 9.6 |
| Standard Deviation | 9.2 | 2.4 | 6.3 | 8.1 | 1.1 | | | 9.8 | 6.2 |
| | | | | Quartz Sandstone Horizon | | | | | |
| G030 | 51 | 7 | 10 | 5 | 1 | 0 | 0 | 25 | 1 |
| F030 | 56 | 11 | 6 | 1 | 0 | 26 | 0 | 0 | 1 |
| W131 | 58 | 8 | 3 | 2 | 1 | 0 | 9 | 17 | 10 |
| Mean | 55.1 | 8.3 | 6.5 | 2.6 | 0.7 | | | 14.2 | 4.1 |
| Standard Deviation | 4.1 | 2.1 | 3.5 | 2.3 | 0.6 | | | 12.9 | 5.3 |
| | | | | Samples with over 20 Percent Zeolite, Prehnite, Calcite | | | | | |
| G015C | 49 | 0 | 1 | 0 | 0 | 0 | 49* | 0 | 1 |
| G032 | 14 | 2 | 6 | 24 | 0 | 0 | 45 | 7 | 3 |
| E004 | 51 | 0 | 0 | 0 | 0 | 0 | 47* | 1 | 1 |
| E022 | 17 | 0 | 13 | 31 | 2 | 0 | 26 | 9 | 2 |
| E026 | 23 | 4 | 28 | 11 | 2 | 0 | 20 | 9 | 3 |
| F042 | 24 | 5 | 21 | 7 | 2 | 27 | 0 | 11 | 3 |
| F530 | 14 | 2 | 17 | 29 | 1 | 29 | 2 | 6 | 1 |
| F532 | 16 | 4 | 10 | 27 | 2 | 0 | 34 | 6 | 1 |

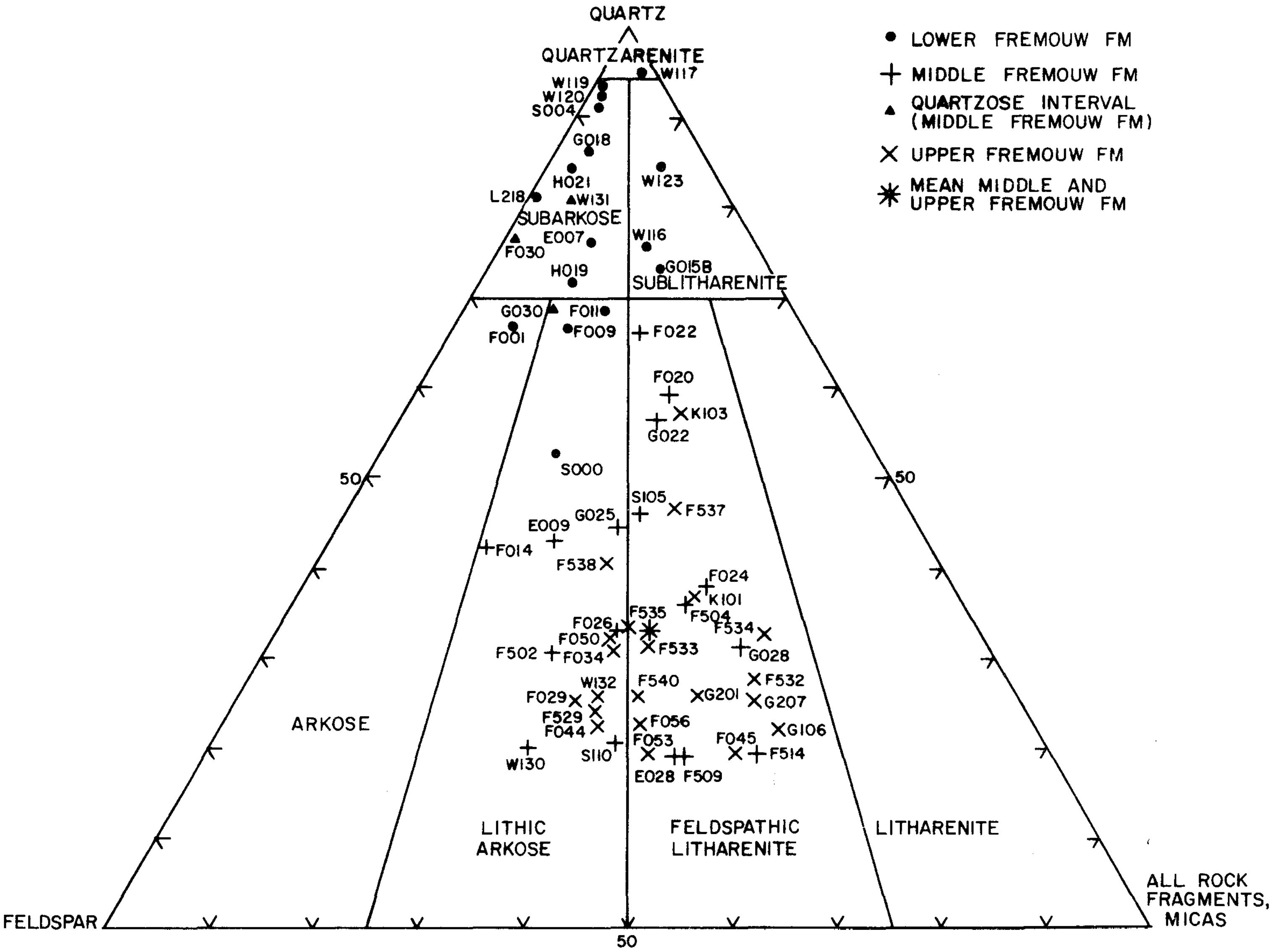



Figure 31. Composition of sandstone samples with less than 20 percent calcite, prehnite or zeolite from the Fremouw Formation.

Formation, but is less than one percent in over half of the samples from the Buckley Formation. In the middle and upper parts of the formation, volcanic fragments are more abundant than other lithic fragments and form an average of 21 percent of the rock. The volcanic fragments are similar to those in the Buckley Formation and have the characters described in Table 3. The other lithic fragments are mainly of fine-grained sedimentary or low-grade metasedimentary origin. Both muscovite and brown biotite are present in small amounts. Most samples contain a little calcite, but in only five samples does it exceed five percent (Table 10). Most sandstones, whether from the lower, middle, or upper part of the formation, are fine to medium grained and moderately well sorted (Table 4).

A "sandstone" bed 282 m above the base of the formation at W1 (Wahl Glacier) was found upon thin section examination to be a vitric tuff (Fig. 32). Although almost 100 thin sections of Fremouw sandstone samples have been examined, no other tuffs have been identified. The form of the glass shards has been preserved by localized calcification in subspherical areas about 1 cm across, which constitute about 20 percent of the rock. Outside of the calcified areas the rock appears very-fine-grained and dark under crossed nicols, but in places shard forms are outlined by fine-grained micaceous flakes. The shards are mostly angular elongate fragments 0.2 mm long, commonly with undistorted partially or completely outlined vesicles about 0.05 mm across. Seven percent of the thin section is clear angular quartz (Table 13). The plagioclase (16 percent) is very cloudy, and locally has been partly replaced by calcite. A few greenish-gray mudstone beds in the middle part of the formation in the Prebble Glacier area (F0, F1) have scattered white rectangular patches one or two millimeters across, which give the rock a volcanic appearance in the field. A thin section (F028) of such a bed was very fine grained, micaceous and had a volcanic aspect, but no specific features to identify the rock as a tuff could be found. The field identification of intermediate to acid volcanic pebbles from the type section (sample F025, p. 52) was confirmed by the examination of thin sections of three pebbles. In one pebble relict flow structure is evident in the ground mass, which is very fine grained, dark under crossed nicols, and has no preferred orientation. The phenocrysts are mainly subhedral to euhedral plagioclase as much as 3 mm long. A few small clear quartz crystals and a variety of small xenoliths of quartz siltstone and chert are also present. Spherulitic chalcedony has replaced large areas of the ground mass, and a chloritic mineral locally replaces plagioclase as well as being scattered through the chalcedony. The other two pebbles are acid tuff, possibly of ash-flow origin. Phenocrysts of cloudy brownish plagioclase and quartz are sparsely scattered through a very-fine-grained low-birefringent crudely-foliated ground mass. One of the two contains a few elongate cloudy brown pleochroic crystals of what now is probably biotite. The other pebble lacks opaque or mafic minerals. The lack of textures or mineral characteristic of regional metamorphism suggests a post-Ordovician age for the pebbles. There is

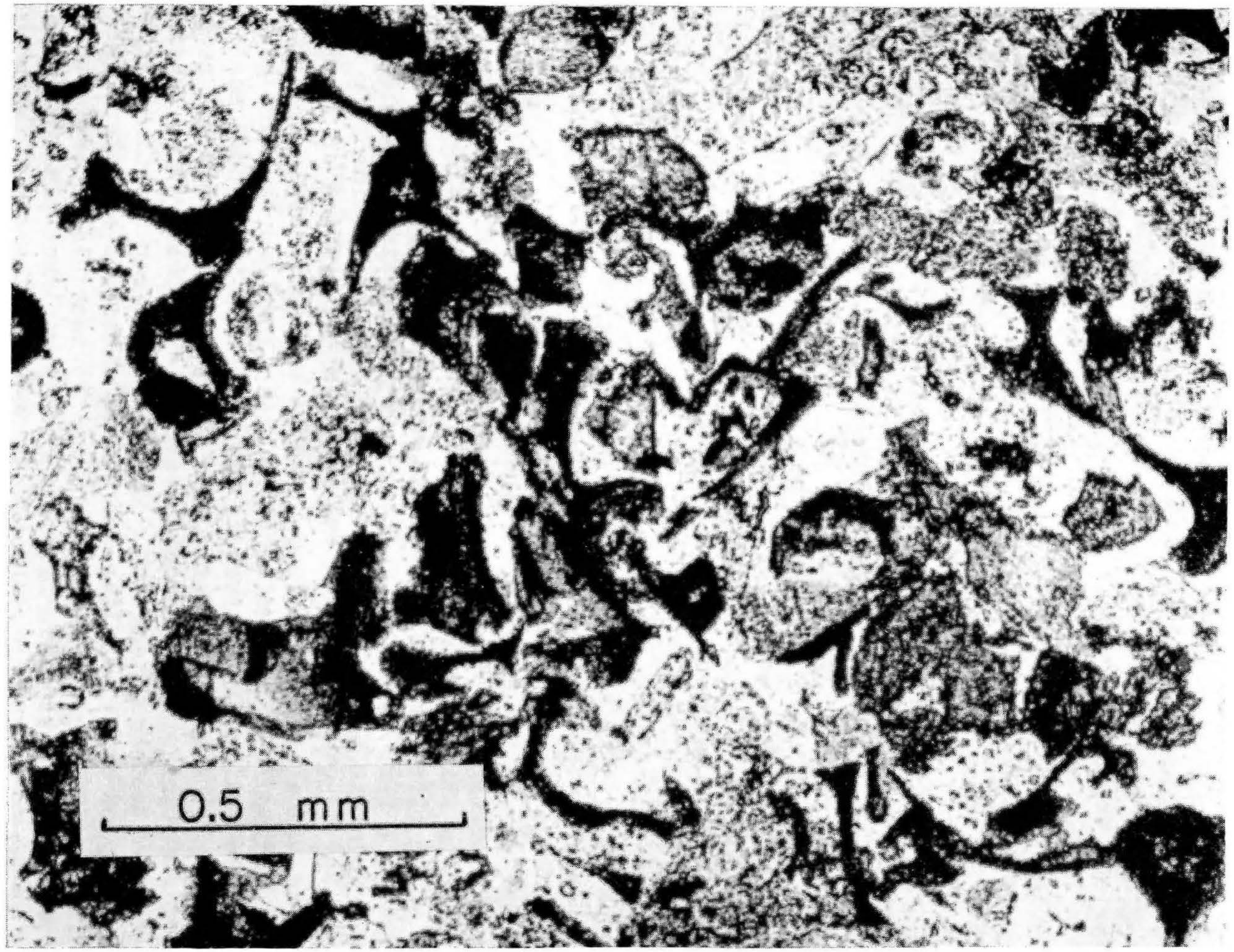



Figure 32. Vitric tuff (W130) from the middle part of the Fremouw Formation Wahl Glacier. The curved forms are glass shards that have been replaced by calcite. Plain light. Photo - J. M. Schopf.

no indication of post-Ordovician and pre-Permian volcanism in the central Transantarctic Mountains, and a Permian or Triassic age for the pebbles is favored.

Zeolite in the Fremouw Formation replaces plagioclase and to a lesser extent rock fragments, and occurs as a cement. Thirteen volcanic sandstones were analyzed by X-ray diffractometer (Table 10). Ten samples, for which point-counts had indicated zeolite percentages from 7 to 34 gave peaks characteristic of laumontite. In the other three samples, whose zeolite percentages are 0,0 and 5, no zeolite was detected. With one exception (below) laumontite is the only zeolite that has been found in beds stratigraphically below the Falla Formation, and it has not yet been identified in samples from the Falla or younger formations. At GO near the base of the sill that caps Graphite Peak, white but locally pink-stained acicular crystals were found in veins in greenish-gray siltstone. The X-ray powder pattern showed the mineral to be stilbite.

Metamorphism in the Fremouw and other formations

The distribution of laumontite and prehnite indicates that most strata in the Fremouw and older formations belong to the laumontite-prehnite-quartz facies of metamorphism (Winkler, 1967), for which Winkler has suggested a temperature range of 200 to 400°C. The present thickness of strata above the top of the Fremouw Formation in the central Queen Alexandra Range is about 1 km, and the overlying basalts may have been as much as 2 km thicker (McGregor, 1965). These thicknesses are much lower than those normally required for the initiation of burial metamorphism; for these Beacon rocks metamorphism appears to have been dominantly thermal and due to diabase intrusion.

Jaegar (1967) has calculated that a diabase sill raises the temperature at its contact by 665°C, and within a distance equal to one tenth its thickness by 580°C. Laumontite is found in volcanic sandstone (B200) as close as 3 m from a thick sill, but Koizumi and Roy (1960) have found that even isolated laumontite breaks down at 410°C and 1000 bars $P_{H_2O}$ after only a few days. Coombs and others (1959) have found laumontite to be unstable in the presents of quartz above about 320°C. It seems, then, that near sills laumontite formed during the cooling of the strata and well after the maximum temperature had been reached.

Primary structures

Trough-cross-bedding is common in many sandstone units, but the thick sandstone beds in the upper part of the formation are mainly parallel-bedded or have low-angle discordant bedding. Lenses of mudstone fragments are commonly associated with the erosion surface defined by the low-angle discordances, but when traced laterally, most pinch out into massive sandstone. Microcrosslamination is common in fine-grained sandstone stringers within coarser beds, and in the very-fine-grained sandstone beds, but few ripple marks were seen.

Sole marks are common on erosion surfaces at the base of the quartzose sandstone units, occurring generally as elongate depressions 2 or 3 cm long. Larger and more spectacular "comet-shaped" scour features (Fig. 33) were found at the base of the coarse-grained subarkose 294 m above the base of the type section (FO). These forms are about 30 cm across and 10 cm high at the "head" and have a raised tail at least a meter long that tapers in the downstream direction. Although the tails of these forms point to 0°, cross-bedding indicates a flow direction of 320° for the current depositing the overlying sandstone.

### Paleontology

Most of the traces of invertebrate life were found at GO, SO, and W1, where subarkose beds in the lower part of the formation contain burrows with a circular cross section from 5 to 10 mm in diameter (Fig. 34). Most are perpendicular to the bedding plane, although some lie in it. Trials also were noted at W1, where they are about 10 cm across and more than 30 cm long. Similar burrows are common in the middle part of the formation at GO, but elsewhere they have been found only at one level at S1 and at EO.

The discovery of the left posterior part of the lower jawbone of a laybrinthodont amphibian (Fig. 35) at Graphite Peak, in subarkosic sandstone 76 m above the base of the Fremouw Formation, by the writer accompanied by David Johnston, has been described and evaluated (Barrett and others, 1968a). No closer identification has been made. The mold of a gastropod (Fig. 36) was found in burrowed strata at the top of the same subarkosic sandstone.

Features thought to be calcified roots and rootlets are common in the upper part of the Fremouw Formation. The most common variety consists of more or less vertical sinuous rods about 5 mm across, extending down as much as 60 cm from the upper surfaces of some fine-grained sandstone and mudstone units. No forms with the internal structures preserved have been found, but in sample FO28 from Fremouw Peak the surface of a vertical rod 1 cm in diameter has fine striations (about 8 per millimeter) parallel to the plant axis. This, together with the common association of these root-like forms with longitudinally-striated stems, suggests that the roots and stems might belong to the same reed-like plant. Root horizons have been found in all stratigraphic sections through the middle and upper parts of the formation except at W1, and appear, at EO, as low as the lowest greenish-gray siltstone, 2 m above the base of the formation. However, they are not common low in the formation and in most places do not appear in the lower 200 m.

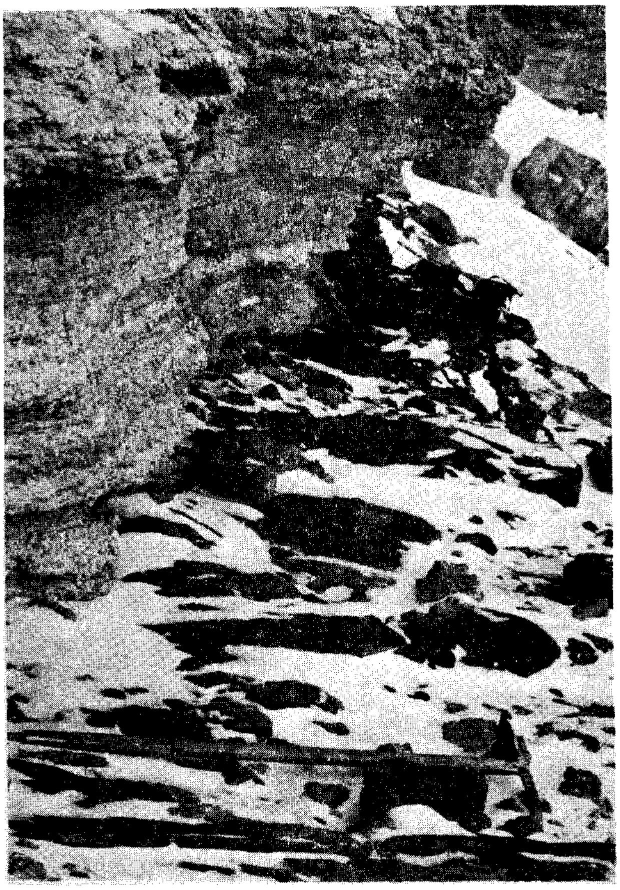
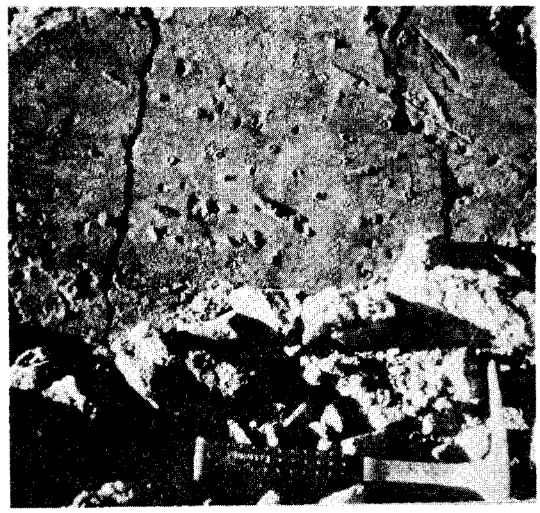


Figure 33. (left) Scour forms at the base of the subarkose 294 m above the base of FO, Fremouw Formation, Prebble Glacier. The ice axe points in the inferred current direction.

Figure 34. (below) Burrows exposed on a bedding plane 77 m above the base of the Fremouw Formation at Graphite Peak (GO).



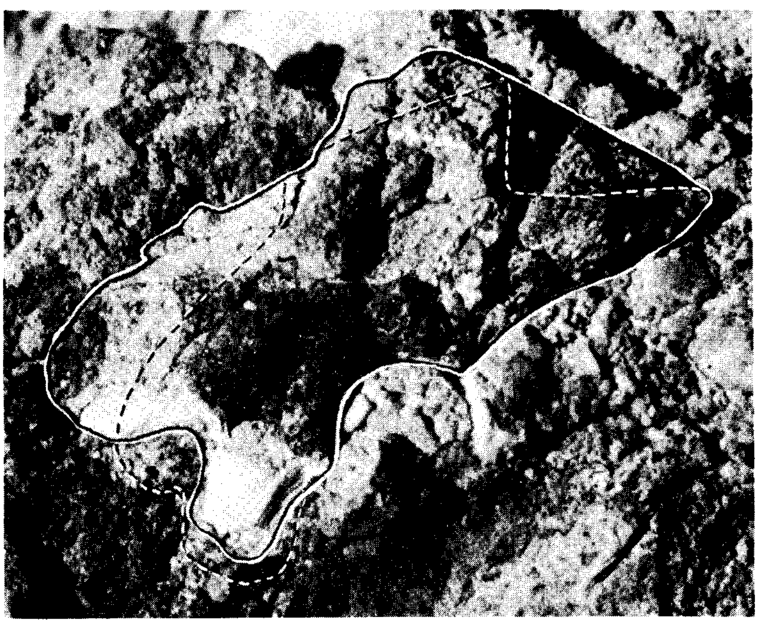


Figure 35. Labyrinthodont jawbone fragment in place 76 m above the base of the Fremouw Formation at Graphite Peak (GO). The bone is 7 cm long. The full outline delimits the bone; the dotted outline indicates the extent of the fragments recovered. The outlines were drawn at the American Museum of Natural History.


Figure 36. Mold of a gastropod in subarkose 77 m above the base of the Fremouw Formation at Graphite Peak.

Scattered irregular threads or flecks of white calcitic material in fine-grained sandstone and greenish-gray siltstone that characterizes the lower and middle Fremouw Formation are thought also to represent root remains. They are particularly well-preserved near the base of F5, and at G0 (Fig. 37).

Plant stems with fine longitudinal striae alternating at the nodes, probably Neocalamites, are common at several levels in the upper 300 m of the formation in the Prebble Glacier area, although at F5 the stems appear as low as 430 m below the top of the formation. The stems have a similar distribution at Mount Kinsey (E0) and at Graphite Peak (G0, G1, G2) east of the Beardmore Glacier.

Logs as much as 1 m across are exposed in a sandstone 30 m below the top of the formation on the south slopes of Fremouw Peak and in a col just north of the peak, where some are as much as 22 m long (Fig. 38). Several stumps about a meter across are in growth position in the sandstone. The growth rings are well-developed, indicating a strongly seasonal climate, and vary considerably in width. Dr. J. F. Lindsay (oral communication) counted 239 rings over a radius of 67.5 cm in one log. Thin section examination by Dr. J. M. Schopf has revealed well-preserved cell structure in primary and regenerative tissue. In one sample logs were found in the upper 100 m of the formation also at Mount Kirkpatrick (K1), Kenyon Peaks (T0), and near Graphite Peak (G2) 160 m below the top of the formation.

Dicroidium odontopteroides has been identified (Rigby and Schopf, 1967) from leaves in a silt lens in sandstone exposed in the same col in which the large logs described above were found.

Correlation and age

The only likely known lithologic equivalent of the Fremouw Formation north of the Beardmore Glacier area is the Ellis Formation (Haskell and others, 1965) in the Darwin Glacier area. The Ellis Formation consists of 30 m of light-colored quartzose sandstone with stringers of green sandstone, white siltstone, and quartz pebbles, and is separated from the underlying Permian coal measures by a diabase sill 30 m thick.

The Fremouw Formation is probably equivalent, in part at least, to a 565-m-thick unit that Wade and others (1965) described from above the Buckley Coal Measures at Mount Kenyon on the Shackleton Glacier. The strata consist of massive cross-bedded sandstone with a subequal proportion of gray to dark-gray silty shale interbeds, and were considered by the authors to be equivalent to Grindley's Falla Formation, although the substantial lithologic differences were recognized.

Strata assigned to the Dominion Coal Measures by Wade and others consist of carbonaceous shale and sandstone overlain by thick

Figure 37. Replaced roots and rootlets in greenish-gray siltstone in the upper part of the Fremouw Formation near the top of the Graphite Peak section (GO).

Figure 38. A log 22 m long embedded in sandstone in the col just north of Fremouw Peak, Prebble Glacier.

coarser grained sandstone, which contain, in the lower part, leaves of Dicroidium and logs and stems. These beds may be equivalent to the upper part of the Fremouw Formation or to the lower part of the overlying Falla Formation.

The Fremouw Formation is thought to be Triassic in age. Dicroidium odontopteroides indicates a Triassic age (Rigby and Schopf, 1967; Townrow, 1967) for at least the upper part, and the entire underlying Buckley Formation probably is Permian (p. 47). The Permian-Triassic boundary, therefore, is probably at the base, but may lie somewhere in the lower part of the formation.

Although a Permian age was given by Wade and others (1965, p. 16) to beds on Mount Kenyon assigned by them to the Falla Formation, the plant material probably is Triassic (Schopf, oral communication) because of some similarities to better-preserved forms associated with Dicroidium in collections from higher in the stratigraphic section.

Environment of deposition and source

The erosion surfaces, mudstone fragments, trough-cross-bedded sandstone and the "fining-upwards" cycles indicate a flood plain environment of deposition for the Fremouw Formation. The root impressions in the lower and middle parts of the formation at Mount Kinsey and McIntyre Promontory and the tree stumps at Fremouw Peak show that vegetation grew throughout the deposition of the formation in the Beardmore Glacier area. However, little plant material was preserved until the upper part of the formation was deposited.

Although the broad environment of deposition was probably about the same as for the underlying Buckley Formation, the differences in proportion of sandstone and in the amounts of carbonaceous material indicate a change in some factors, perhaps including climate, in the environment. McGregor (1965), who first recognized the similarity in style of deposition between the Buckley Formation and the overlying strata, suggested that "the climate was too arid for plant growth during the deposition of the Falla [here lower and middle Fremouw Formation]." However, roots and stems have now been found at several levels in the lower and middle Fremouw Formation.

The sources for the non-volcanic Fremouw sand was to the southeast (Fig. 4), in contrast to sources to the north and west for the underlying Buckley Formation. The source area for the lower part of the Fremouw Formation was much more quartzose than was the source area for the Buckley Formation, and K-feldspar reappeared as a regular constituent of the sediment. In the middle and upper parts of the formation, intermediate to acid volcanic detritus diluted the quartzo-feldspathic sand considerably, although not overwhelmingly as in many sandstone beds in the Buckley Formation. Most of the volcanic material, which is of pyroclastic and flow origin, was reworked by streams before burial, but one ash fall was found in the middle part of the Fremouw Formation. The quartzose source to the southeast was the only source for a small interval in the middle part of the formation, and then it diminished in importance again until the beginning of Falla Formation deposition.

## Falla Formation

### Background

The Falla Formation was named by Grindley (1963, p. 335) for strata "overlying the Buckley Coal Measures, typically exposed on Mount Falla in the central Queen Alexandra Range. The type locality is the north-facing cliff section of Mt Stonehouse, [now called Golden Cap] a 9,350 ft [2850 m] peak 5 miles [8 km] west of Falla, and the ridge leading from Stonehouse to Falla". Grindley stated that the lower part of the formation consists of "a basal quartz arenite, 400 ft [120 m] thick, overlain by well bedded, medium-grained, micaceous and slightly carbonaceous grey sandstone, 300 ft [90 m] thick. The upper part, some 1,600 ft [500 m] thick, consists of an alternating sequence of clastic, fresh-water sediments ranging from lensoid quartz-pebble conglomerates through grey-green quartzo-feldspathic sandstones to well bedded grey-green siltstones." The base of the "alternating sequence" is easily recognized in the field by the change from slope-forming sandstone units below to bluff-forming units above, and was measured at 580 m stratigraphically below the base of the Kirkpatrick Basalt (comparable with Grindley's estimate of 500 m).

Although 17 m of subarkosic sandstone do crop out at the base of F3 about 300 m stratigraphically below the base of Grindley's upper Falla Formation, the two units of quartz arenite and medium-grained sandstone, as described by Grindley, were not recognized in the two stratigraphic sections (F3 and F5, about 3 km apart) measured by the writer at the type locality, or in the section on nearby Fremouw Peak (F0). In fact, the section on Fremouw Peak extends for over 600 m stratigraphically below the base of Grindley's upper Falla Formation, and has been described here separately as the Fremouw Formation.

### Definition

It is proposed that the name Falla Formation be restricted to the upper Falla Formation of Grindley (1963), which consists of a cyclic sequence of light-gray reddish-brown-weathering fine- to medium-grained sandstone, greenish-gray and gray carbonaceous fine-grained sandstone and shale, and light-greenish-gray tuff in the upper part of the section. The proposed type section (F2, Fig. 39) which is 530 m thick, starts at the lowest bluff-forming reddish-brown-weathering sandstone at a point 3.2 km northwest of the summit of Mount Falla, near the base of the north face at the west end (84° 21.0' S; 164° 42' E). The upper boundary of the formation here is the base of the paraconglomerate (poorly sorted open-framework conglomerate) that underlies the Kirkpatrick

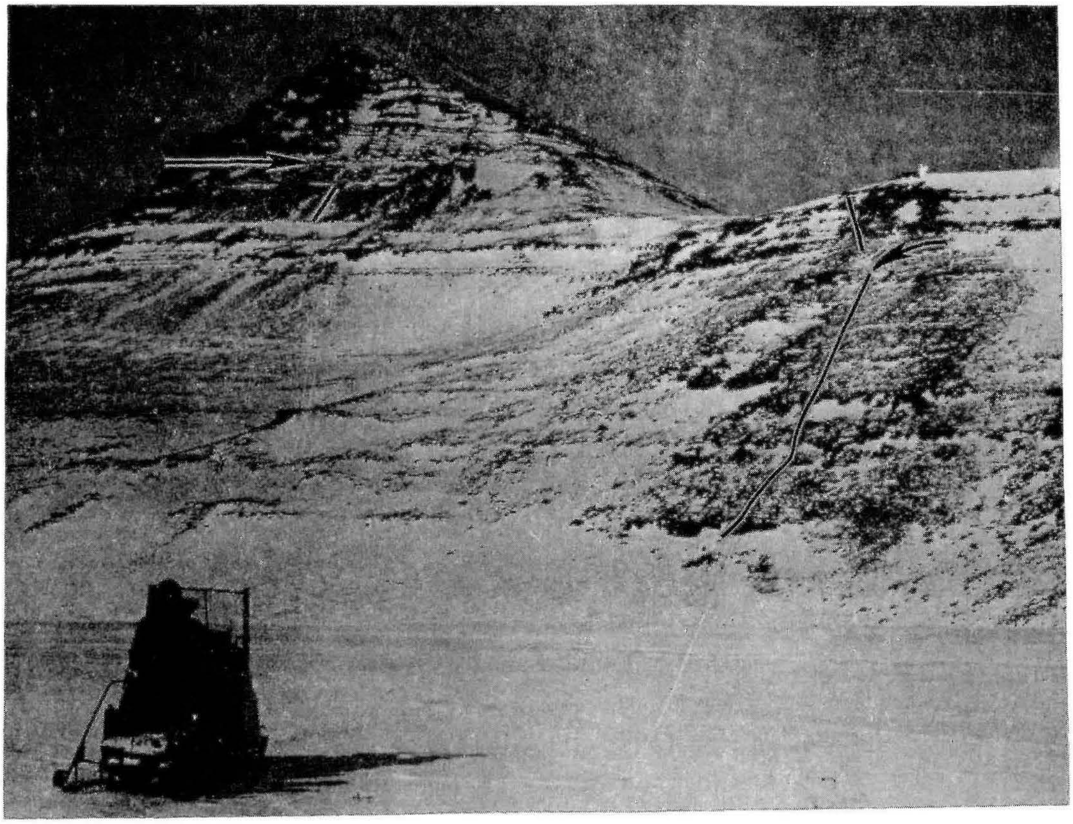


Figure 39. North face and west ridge of Mount Falla, central Queen Alexandra Range. The black line indicates the type section of the Falla Formation (F2). The lowest known tuff bed in the section and the base of the Kirkpatrick Basalt are arrowed.

Basalt in the north face of Mount Falla (84° 21.7' S; 164° 50' E).

Distribution and thickness

The Falla Formation in the Queen Alexandra Range extends as far southward as the Marshall Mountains. At Kenyon Peaks (T1) it is 158 m thick, contrasting with the 530 m measured on Mount Falla. A thickness of 283 m was measured on Mount Kirkpatrick, the northernmost outcrop of the formation known. East of the Beardmore Glacier the Falla Formation is known only from one outcrop. Near Graphite Peak an inclusion of quartzose sandstone 30 m thick lies within the lower part of a diabase sill at the top of G2. The beds beneath the sill are typical of the uppermost Fremouw Formation (p. 53) and the more quartzose sandstone above is thought to be equivalent to the Falla sandstone in the type area, where the Falla sandstone is also considerably more quartzose than sandstone in the underlying upper Fremouw Formation.

Stratigraphic sections from the northern Dominion Range (McGregor, 1965) contain no indication that beds as young as the Falla Formation have been preserved there.

Lower contact

The lower contact of the Falla Formation in the Prebble Glacier area is disconformable at F3; at F0, F2 and F5 it was covered with snow or scree. The contact is readily recognizable from a distance in the Queen Alexandra Range, for it is marked by a change from slope-forming sandstone with a greenish cast (Fremouw Formation) to the reddish-brown bluff-forming sandstone ledges of the Falla Formation, reflecting the lower quartz content of the upper strata of the Fremouw Formation.

Lithology

The lower 270 m of the Falla Formation at the type section consist of a sequence of 12 cycles, mostly of sandstone and shale, from 5 to 54 m thick (average 23 m). Each cycle begins with a massive light-gray (reddish-brown-weathering) fine- to medium-grained sandstone, which overlies an erosion surface with less than 30 cm of relief. Discoidal shale fragments as much as 40 cm across were found in the lower meter of all but three cycles; rounded pebbles, mainly of vein quartz, (F206, Table 12) and generally less than 2 cm across, were found near the base of two cycles. Locally, the clasts occur higher in the basal sandstone of each cycle. The basal sandstone in each cycle normally grades up in into greenish-gray fine-grained sandstone and then into carbonaceous shale. In some cycles high in the section the greenish-gray sandstone is missing.

This cyclic sequence is overlain by three alternations, totalling 80 m in thickness, of sandstone and vitric tuff. The sandstone beds are similar to the basal sandstone beds of the underlying cycles, and two of the three sandstones have white quartz pebbles in the lower meter. Pebbles as much as 14 cm long and of white quartz, metasedimentary and volcanic rocks (Table 12, F218A) form a band 10 cm thick and 11 m above the base of the lowest sandstone. The tuff is light greenish gray, massive to medium bedded, and in the field resembles a very-fine-grained sandstone. There are two "vesicular" or pitted horizons about 30 cm thick in the upper part of the lowest tuff bed. Sandstone similar to the basal sandstone units lower in the section separates the lowest tuff bed from a similar tuff above that is 11 m thick.

The beds from 340 to 420 m above the base at the type section consists almost entirely of tuff (Fig. 40), which is generally massive, light greenish gray and very fine grained. A total of 13 beds of tuff from 10 cm (Fig. 41) to 12.5 m thick and two interbedded sandstone units totalling 12 m in thickness were distinguished in this interval. Most of the units are weather resistant, and together they form a prominent bluff (Fig. 40) that extends from the west ridge of Mount Falla around the north face below the Kirkpatrick Basalt. Features found in only one or two of the units include scattered amygdales as much much as 2 cm long and 0.6 cm across, lying parallel to the lower contact of the unit; concretionary structures from 3 to 8 cm across distinguished by a black rim several millimeters thick; and in the uppermost unit evenly spaced columnar joints from 15 to 30 cm apart. Two units contain abundant green fine-grained lenticles 1 to 2 cm across. Red-stained analcime fills small cavities and veins, giving many of the units a red-speckled appearance.

The upper 113 m of the formation, most of which lies beneath a veneer of basalt scree on the north and west faces of Mount Falla, consist entirely of massive to shaly greenish-gray or light-brown tuff. A few specks of red analcime were found in the lower 24 m and there are amygdales between 23 and 30 m above the base of this interval. In the upper 70 m of the formation accretionary lapilli (Fig. 42) about 1 cm across are common. The upper 1.2 m of the formation, which is separated from the beds below by a snow-covered interval 6 m thick, is sandy, and grades through alternating sandstone and fine-grained conglomerate into the massive paraconglomerate of the overlying Prebble Formation.

The lower part of the Falla Formation of F0 and F3 is similar to the type section, but at the more distant sections on Mount Kirkpatrick and Kenyon Peaks, where the total thickness is known to be less, there are notable differences. No carbonaceous shale was found, and the formation is dominated by light-gray massive fine-grained tuff that weathers white or green, gray, yellow and brown. In the upper part of the formation on Mount Kirkpatrick specks of red-stained analcime are common at several levels, at least one level is amygdaloidal, and one 21-m-thick unit is columnar jointed in the lower 60 cm. Sandstone, which makes up 30 percent of the section on Mount Kirkpatrick, is similar to that at Mount Falla. Rounded white quartz pebbles, mostly less than

Figure 40. Massive to medium-bedded resistant tuff beds about 365 m above the base of the Falla Formation at the type section (F2). In the background dark cliffs of Kirkpatrick Basalt form the summit of Mount Falla.

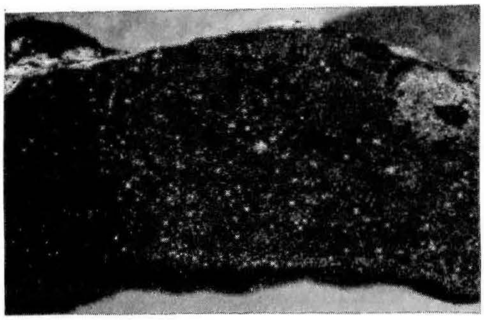


Figure 42. Section through accretionary lapilli in tuff (F249A) 470 m above the base of the type section of the Falla Formation. Photograph is about 3 cm wide. Photo - O.S.U.

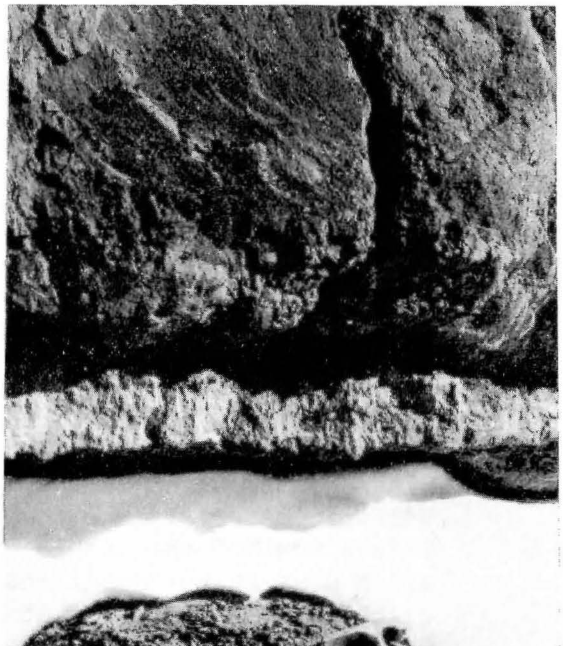


Figure 41. (left) A bed of vitric tuff 10 cm thick between two thicker tuff beds 350 m above the base of the Falla Formation on Mount Falla.

2 cm across, together with red garnet grains, are common near the base of three of the sandstone units. Also, at KO, 246 m above the base of the formation, there are lenses as much as 60 cm thick of pebbles about 2 cm across which are composed of intermediate or acid volcanic rock, vein quartz and several other lithologies (Table 14).

Table 14. Composition of pebble samples (in percent) from the Fremouw and Falla Formations. Numbers of pebbles are in parentheses.

| Sample Number | Qtz | Qtzite* | Chert | Volc | Gwacke | Schist+ | Congl |
|---|---|---|---|---|---|---|---|
| F025 (Fremouw Fm.) | 32 | 6 | 2 | 54 | 2 | 3 | 1 (105) |
| F206 (Falla Fm.) | 78 | - | - | 3 | 4 | 15 | - (143) |
| F218A (Falla Fm.) | ** | 31 | 13 | 34 | 3 | 13 | 6 ( 32) |
| K027 (Falla Fm.) | 5 | 3 | 3 | 59 | 9 | 20 | 1 (106) |

*includes some feldspathic sandstone
+includes argillite
**vein quartz abundant but not collected.

## Petrography

The Falla Formation differs from the Fremouw Formation in the more quartzose resistant character of its sandstone, particularly in the lower part of the formation, where the quartz content is normally higher than 45 percent (Table 15, Fig. 43). The feldspar is mostly plagioclase, which is about three times as common as the K-feldspar. Volcanic material like that in the Buckley and Fremouw Formations comprises most of the lithic fragments. In the type section (F2), from which most of the modal analyses came, there is a clear trend of quartz dilution with time, and at Mount Kirkpatrick the much lower quartz content of samples high in the formation is evident too. Falla Formation sandstone is generally fine- to medium-grained and moderately well sorted.

Table 15. Modal analyses (in percent) for samples from the Falla Formation. Numbers in parentheses are percentages of volcanic fragments.

| Sample | Quartz | K-Spar | Plag | Lithic | Mica | Calcite | Zeol | Matrix | Rest |
|---|---|---|---|---|---|---|---|---|---|
| T104 | 56 | 11 | 13 | 10 (6) | 0 | 0 | 0 | 8 | 2 |
| F063 | 48 | 5 | 15 | 16 (8) | 2 | 0 | 0 | 12 | 2 |
| F064 | 44 | 0 | 22 | 14 (5) | 2 | 0 | 0 | 15 | 3 |
| F067 | 38 | 0 | 24 | 19 (12) | 4 | 0 | 0 | 10 | 3 |
| F406 | 42 | 7 | 18 | 15 (12) | 4 | 0 | 0 | 8 | 6 |
| F201 | 60 | 3 | 9 | 16 (9) | 1 | 0 | 1 | 7 | 3 |
| F213 | 51 | 4 | 20 | 10 (6) | 3 | 1 | 0 | 9 | 1 |
| F215 | 44 | 5 | 22 | 18 (14) | 2 | 0 | 0 | 6 | 3 |
| F216 | 37 | 4 | 24 | 21 (13) | 2 | 0 | 0 | 8 | 4 |
| F217 | 29 | 5 | 25 | 24 (13) | 4 | 0 | 0 | 12 | 2 |
| F222 | 57 | 10 | 18 | 9 (5) | 0 | 0 | 0 | 4 | 1 |
| F225 | 47 | 8 | 20 | 12 (7) | 2 | 0 | 0 | 9 | 1 |
| F541 | 48 | 4 | 20 | 15 (7) | 2 | 0 | 0 | 9 | 2 |
| K004 | 43 | 11 | 14 | 10 (6) | 3 | 0 | 3 | 14 | 6 |
| K006 | 42 | 3 | 10 | 15 (11) | 1 | 0 | 2 | 26 | 4 |
| K008 | 52 | 13 | 5 | 8 (7) | 0 | 0 | 2 | 17 | 5 |
| K025 | 25 | 4 | 14 | 34 (18) | 1 | 0 | 16 | 3 | 20 |
| K028 | 37 | 3 | 14 | 33 (23) | 0 | 0 | 1 | 8 | 6 |
| Mean | 44.5 | 5.6 | 17.0 | 16.7 | 1.8 | 0.1 | | 10.3 | 4.1 |
| Standard Deviation | 9.3 | 3.7 | 5.7 | 7.4 | 1.3 | 0.4 | | 5.2 | 4.2 |
| Samples with over 20 percent calcite and zeolite | | | | | | | | | |
| G208 | 48 | 6 | 4 | 10 | 0 | 0 | 24 | 5 | 27 |
| F208 | 52 | 6 | 9 | 6 | 0 | 25 | 0 | 1 | 0 |
| F214 | 33 | 3 | 13 | 19 | 3 | 23 | 0 | 5 | 1 |

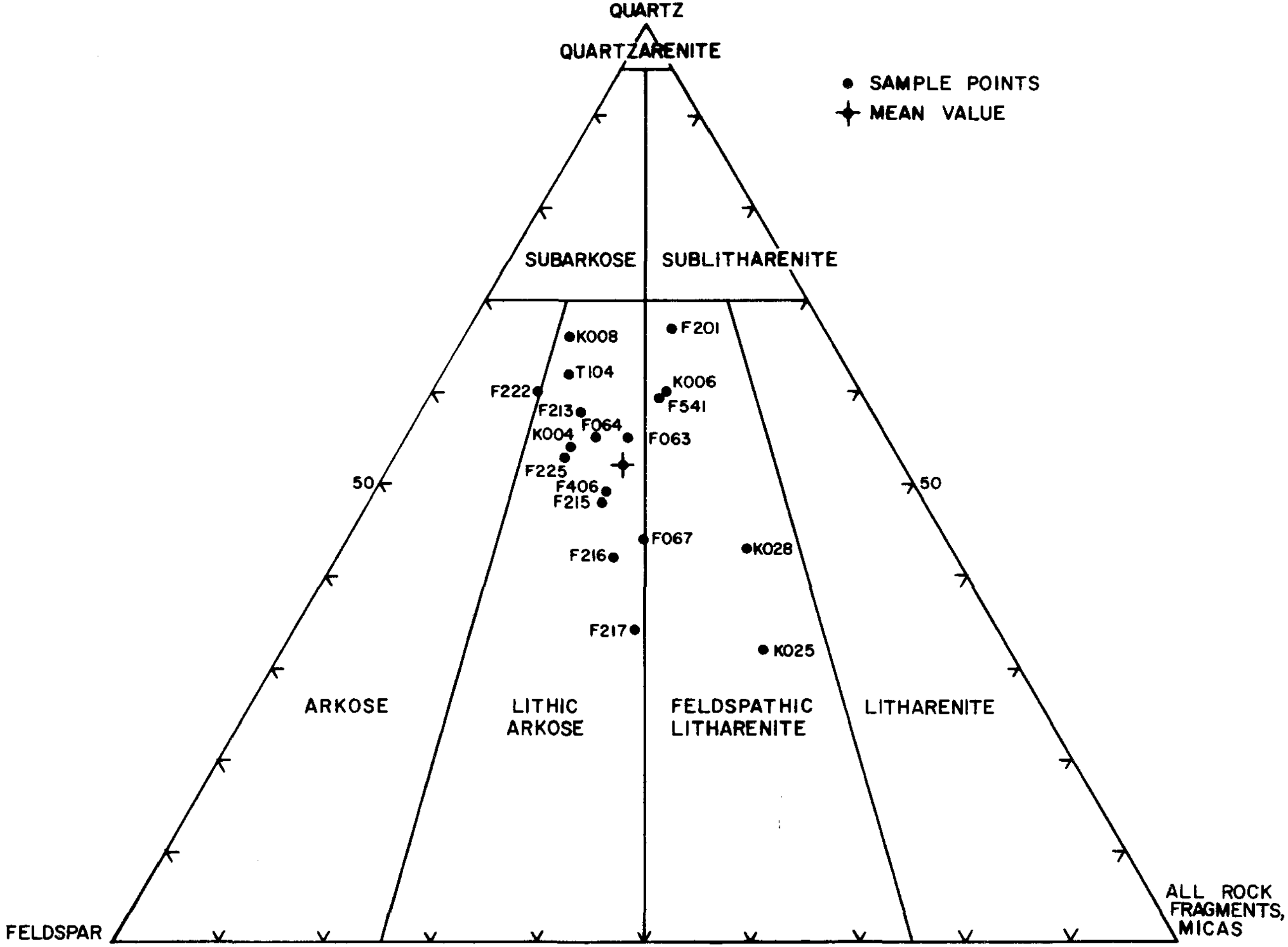



Figure 43. Composition of sandstone samples with less that 20 percent calcite or zeolite from the Falla Formation.

The dominance of volcanic ash in the upper part of the Falla Formation at the type section, and most of the formation at KO and T1, became evident mainly from thin section study. Most of the tuff beds are composed of coarse silt size grains set in a fine-grained low birefringent irresolvable matrix. Scattered through the matrix are shards of fresh slightly devitrified or zeolitized glass, together with the less common fragments of quartz and plagioclase. A little anorthoclase has also been found. The thin and complicated shard forms, some of which have curved reentrants, are most easily recognized where they are stained pink (F239, F246). Lower in the section (F220, F226), a greenish tint and low birefringence in some of the shard forms suggests incipient chloritization. Heavy minerals are rare and so far only a little biotite, muscovite, and scattered opaque minerals have been found. Indications of hot deposition, such as collapsed vesicles and welded shards, were found only in one fragment in sample K020 from Mount Kirkpatrick. The sample comes from the base of a tuff unit in which the lower 60 cm is columnar-jointed, a feature of welded ash beds. The same sample contains fragments of pumice a centimeter across as well as rare microcline and fine-grained sedimentary or metasedimentary grains. Fragments of pumice or of fine-grained tuff were found in samples of a number of units on Mount Falla.

Zeolites in the Falla Formation occur mainly in tuff beds and as sandstone cement. Optical properties and X-ray diffractometery (Table 10) showed the red specks scattered through ash beds and in joints on Mount Falla to be analcime. The seven tuff samples analyzed gave very strong quartz and strong, but less prominent, feldspar peaks. Analcite, clinoptilolite and mordenite were all positively identified in different samples. Clinoptilolite is the only major component besides quartz and feldspar in K025, a zeolite-cemented sandstone.

Chemical analyses (Barrett, in preparation, b) indicate that in spite of the lack of K-feldspar the tuffs have the composition of soda rhyolites.

The highest major rock unit in the Falla Formation both in the type section and at Kenyon Peaks (T1) is a bed, clearly tuffaceous in the lower part, that contains in the middle and upper parts round or slightly oblate spherules, as much as 1 cm across, with a thin black shell (Fig. 43). They fit well the description given by Moore and Peck (1962) of accretionary lapilli in volcanic rocks of the western continental United States. Each lapillus has a distinct core with a radius of from 74 to 82 percent of the total (based on four cross-sections). In this core subequal proportions of quartz and feldspar, mostly of coarse silt size but with grains as long as 0.4 mm, float in a very-fine-grained low birefringent matrix. The core grades rapidly over only 0.1 or 0.2 mm into a much finer grained "mantle." Grains in the mantle rarely exceed 0.01 mm in diameter. In a thin section from Kenyon Peaks, 30 m below the base of the lowest basalt flow, the mantle material has the same optical orientation as the matrix, but in a thin section from

115 m below the basalts on Mount Falla (F249A) the average optical orientation in the mantles is parallel to the rims of the lapilli, in contrast to the consistent planar orientation of the matrix. The orientation in the latter sample is clearly primary; that in the Kenyon Peaks sample may have resulted from contact metamorphism by the overlying flow. Within the mantle a decrease in grain size and an increase in opacity toward the rim is evident in all of the lapilli examined. In some the concentration of fine opaque dust toward the rim is sufficient to produce a dark shell as much as 0.10 mm thick. Both tin sections examined contained fragments of broken lapilli, mainly pieces of mantle and shell. Moore and Peck (1962, p. 190) give a well-documented argument as well as references to observations of lapilli formation during volcanic eruptions for the origin of these structures from "Clouds of ash rich in water vapor [which] form during volcanism, mostly during phreatic eruption of basaltic ash....or during Pelean eruptions of rhyolitic and andesitic ash..." The main implications of the occurrence of lapilli are:

a. Deposition on land or possibly in very shallow water, for otherwise the lapilli, which are held together by moisture, would have disintegrated, and

b. Derivation "very likely....within 100 miles or so of the deposit, and probably....within about 10 miles." (ibid., p. 191).

Three volcanic pebbles from the type section of the Falla Formation (sample F218A, Table 12) were sectioned. In one section phenocrysts as much as 1.2 mm long, mainly of plagioclase but with smaller less common K-feldspar and quartz crystals, are set in a groundmass with a complex scroll-like flow texture in places accentuated by quartz-filled vesicles. The groundmass, which is slightly birefringent, shows no preferred optic orientation, emphasizing its lack of metamorphism. Another volcanic pebble consists of scattered plagioclase phenocrysts as much as 3 mm long in a holocrystalline groundmass of plagioclase microlites ($An_{30}$). Mafic and opaque minerals are rare. Chemical analysis (Barrett, in preparation, b) indicates that the rock is a trachyte. The third pebble consists mainly of an altered low-birefringent cloudy groundmass, parts of which have a wavy extinction. Two amygdales in the thin section are lined with radiating aggregates of chalcedony and filled with coarsely crystalline quartz. Again mafic and opaque minerals are rare. As with the pebbles from the Fremouw Formation (p. 61), a Permian or Triassic age is favored.

### Primary structures

Many of the sandstone units in the Falla Formation are trough-cross-bedded, and some show parting lineation. Microcrosslamination is common in the finer grained beds.

Paleontology

Leaves of Dicroidium and associated plants were collected from three localities. The best preserved specimens are from a shale 135 m above the base of the type section (F2). Some of the leaves are brown due to the presence of cuticles that can be peeled away from the rock. Carbonified impressions were found also at FO, 83 m above the base of the formation; and at KO, 31 m above the base of the formation.

Correlation and age

The first report of Triassic plants in Beacon strata was by Warren (in Gunn and Warren, 1962), who described a mudstone and sandstone sequence at least 300 m thick from near the head of the Wright Valley, south Victoria Land. The strata contain a number of elements of the Dicroidium flora, and may correlate with either the Fremouw or the Falla Formation.

The Nilsen Formation (Long, in preparation), in the Amundsen Glacier area, 400 km southeast of the Queen Alexandra Range, also may be equivalent to either the Fremouw or the Falla Formation. The Nilsen Formation is an alternating sandstone and shale sequence with some conglomerate that includes acid volcanic and sedimentary pebbles, and overlies Permian coal measures disconformably. Long noted that cross-bedding from the Nilsen Formation indicated a northwest-dipping paleoslope, in contrast to the southeasterly direction that he observed in the underlying Permian beds, a change identical with that documented here (Fig. 4).

In the Beardmore Glacier area the stratigraphy has become somewhat complicated because the complete sequence was not known when the beds above the Buckley Coal Measures were first described (Grindley, 1963). McGregor (1965) published detailed descriptions of the strata above the Buckley Coal Measures in the Supporters and Dominion Ranges near the head of the Beardmore Glacier, and his correlation of those beds with Grindley's Falla Formation in the Queen Alexandra Range was consistent with the description, but in this writer's opinion, after examining both sequences, they are not equivalent.

The present investigation, which was set up to study the Queen Alexandra Range in much more detail than Grindley had opportunity to, led to the discovery of Dicroidium and coal beds at the type locality of Grindley's Falla Formation. Grindley and others (1965, p. 216) had considered the Falla Formation to comprise "approximately 750 m of unfossiliferous sediments without coal or plant remains." The recent discoveries make the Dominion Coal Measures, which were defined by Grindley and others (1965) on the basis of the appearance of abundant carbonaceous material in the Triassic section, equivalent to as much as the uppermost 265 m of the Fremouw Formation in the type area, depending on where the section is measured (p. 52), and therefore equivalent to the lower Falla Formation of Grindley (1963). The upper part of the Fremouw Formation in the Graphite Peak area also is similar to the

Dominion Coal Measures described by McGregor (1965), although the strata in the Dominion Range contain more coal. Further work may show the Dominion Coal Measures to be equivalent to the lower part of the Falla as well as the upper part of the Fremouw Formation in the Queen Alexandra Range.

The presence of Dicroidium odontopteroides in the lower Falla and upper Fremouw Formations indicates a Triassic age (Rigby and Schopf, 1967; Townrow, 1967). An upper age limit of Lower Jurassic is given by a K-Ar age from the overlying Prebble Formation.

#### Environment of deposition and source

There was little or no change in environment of deposition from the Fremouw into the Falla Formation. Rather, the lithologic change seems to have resulted from a change in the supply of detritus in the lower part of the formation and a change of source, from mainly detrital to mainly volcanic, in the upper part of the formation. An influx of relatively quartzose sand marked deposition of the lowest beds in the formation, the quartzose sand being gradually diluted by volcanic sand as deposition proceeded. Quartzose sedimentary and metasedimentary strata, granitic rocks, and an increasing amount of intermediate to acid flow and pyroclastic rocks provided the sediment, which was transported from the southeast (Fig. 4).

The upper part of the Falla Formation is mainly rhyolitic airfall vitric tuff, locally with accretionary lapilli, from volcanic vents within or adjacent to the Queen Alexandra Range. Streams locally were active during the volcanism, depositing volcanic sandstone and pebbles of volcanic and basement rocks.

### Prebble Formation

#### Definition

The name Prebble Formation is proposed for a unit of paraconglomerate, agglomerate, tuff, and tuffaceous sediment that lies between the tuff beds of the upper Falla Formation and the Kirkpatrick Basalt. The type section on the northwest face of Mount Kirkpatrick (KD, Fig. 44) is at the head of the Prebble Glacier, from which the formation name was taken. The base of the formation is defined as the base of the lowest bed of paraconglomerate or agglomerate in the section; the upper contact is the base of the lowest basalt flow.

#### Distribution and thickness

The Prebble Formation has been found in the central and south Queen Alexandra Range, on the northwest side of the Otway Massif, and 35 km to the east at Mount Pratt. The thickness ranges from a minimum

Figure 44. Type section of the Prebble Formation on Mount Kirkpatrick (KO), looking east from near the base. Lenses of cobbles and boulders can be seen in the foreground and middle distance. The cliffs in the background are of Kirkpatrick Basalt.

Figure 45. Lower contact of the Prebble Formation on Mount Falla (F2), showing the gradation from tuff, below the ice axe, through 60 cm of bedded sediment into massive paraconglomerate.

of 0.3 m in the central Marshall Mountains (Dr. D. H. Elliot, oral communication) to 165 m at KO, in the Queen Alexandra Range. On the Otway Massif, Elliot measured a minimum thickness of 460 m.

Lower contact

The lower contact is exposed in only one of the five sections measured by the writer (Mt. Falla, Fig. 45); there it is gradational. The uppermost unit of the Falla Formation is a fine-grained tuffaceous sandstone that grades up through 60 cm of alternating fine-grained conglomerate and sandstone into massive fine-grained paraconglomerate. Elliot found the lower contact on Lindsay Peak to be unconformable.

Lithology

Most of the rock in the lower 85 m of the formation at the type locality on Mount Kirkpatrick is massive light-reddish- or greenish-gray fine-grained paraconglomerate in beds 3 to 12 m thick, separated by thin beds of light-greenish-gray tuff. Most clasts in the paraconglomerate, here and elsewhere, are very fine grained, discoidal, subangular to subrounded, light green, gray, and reddish brown, and tuffaceous; a few are of carbonaceous shale. Boulders, mainly of light-gray sandstone and as much as 70 cm across, were found in discrete lenses as much as 3 m thick within fine-grained paraconglomerate; normally clasts are less than 5 cm across.

The formation from 85 to 116 m above the base at KO is a light-gray tuff containing scattered accretionary lapilli like those described from the Falla Formation. Scree covers higher beds except for the upper 10 m of the formation, which here consists of 4 m of dark-brown agglomerate, 4 m of purple paraconglomerate, and 2.4 m of purple bedded tuff and tuffaceous sandstone (Elliot, oral communication).

At Mount Falla (F2) the Prebble Formation consists only of reddish-brown paraconglomerate, but at Kenyon Peaks (T1) the lower bed is a 4.5-m-thick agglomerate with quartz-filled amygdales in the lower 30 cm and with clasts up to 27 cm across. The upper surface of the agglomerate has about 30 cm of irregular local relief, and is overlain by 9 m of fine-grained paraconglomerate upon which rests the lowest basalt flow in the section.

In the Prebble Formation at the Otway Massif, about 100 km to the southeast, only massive paraconglomerate is exposed in the 440 m below the 20 m of tuff at the top of the formation (Elliot, oral communication). The upper 190 m of the formation were measured by this writer on the nearby southwest corner of the Massif. The same light-colored but variegated tuff, here between 4 and 15 m thick, is overlain with sharp undulatory contact by a basalt flow 130 m thick. Paraconglomerate dominates the underlying section and consists largely of fragments 2 to 5 cm across of light-colored acidic tuff dispersed through a similar but finer grained matrix. There are also a few fragments of fine-grained dark-chocolate brown basalt and of light-gray fine-grained sandstone. The paraconglomerate here includes two coarse-grained lenses, one and six meters thick (Fig. 46), that are evident only from the concentration of larger cobbles and boulders as much as 80 cm across. Blocks of basalt in these lenses have a weathering rind, emphasized by iron oxide stain, between one and three centimeters thick.

Similar basalt boulders were found at Mount Pratt, 32 km east of the Otway Massif, in two units of paraconglomerate totalling 40 m in thickness. The large clasts in the lower unit are mainly light-gray sandstone; those in the upper unit are mainly basalt and as much as one meter across. The maximum boulder size decreases markedly upwards in this bed, the largest boulders being concentrated in the lower two or three meters.

Petrography

The paraconglomerate of the Prebble Formation, in thin section, is variable but normally consists of volcanic fragments set in a fine-grained fragmental volcanic matrix. The glass fragments are partly devitrified, and some are replaced by zeolite (clinoptilolite) or less commonly analcime, as is some of the matrix. There are also very-fine-grained tuffaceous and porphyritic fragments, and rare pieces of the broken accretionary lapilli. Plagioclase is common, and ranges from fresh to very cloudy; some zoning is present. Quartz grains, which normally form less than five percent of the rock, are largely unstrained, although a few are very strained. K-feldspar, some of which shows polysynthetic twinning, occurs in very small quantities in samples from Mount Kirkpatrick and Mount Falla. Opaque grains that seem to be mainly hematite are common; nonopaque mafic minerals are in most sections represented only by a few flakes of brown biotite. Grains of green hornblende and colorless pyroxene are present but rare.

Most of the tuff beds in the Prebble Formation seem petrographically indistinguishable from those in the upper part of the Falla Formation. However, the tuff at the top of the formation at the Otway Massif is very-fine grained and cherty, with scattered angular grains of clear quartz as much as 0.05 mm across. Only quartz could be identified by X-ray analysis of the sample.

Primary structures

Most beds in the Prebble Formation are massive, but some paraconglomeratic beds possess a crude foliation. Inhomogeneity in the Mount Falla section is suggested by horizontal ledges every 10 m. At Mount Kirkpatrick and the Otway Massif there are lenses of boulders within finer grained paraconglomerate and thin parallel-bedded and laminated sandy and pebbly beds.

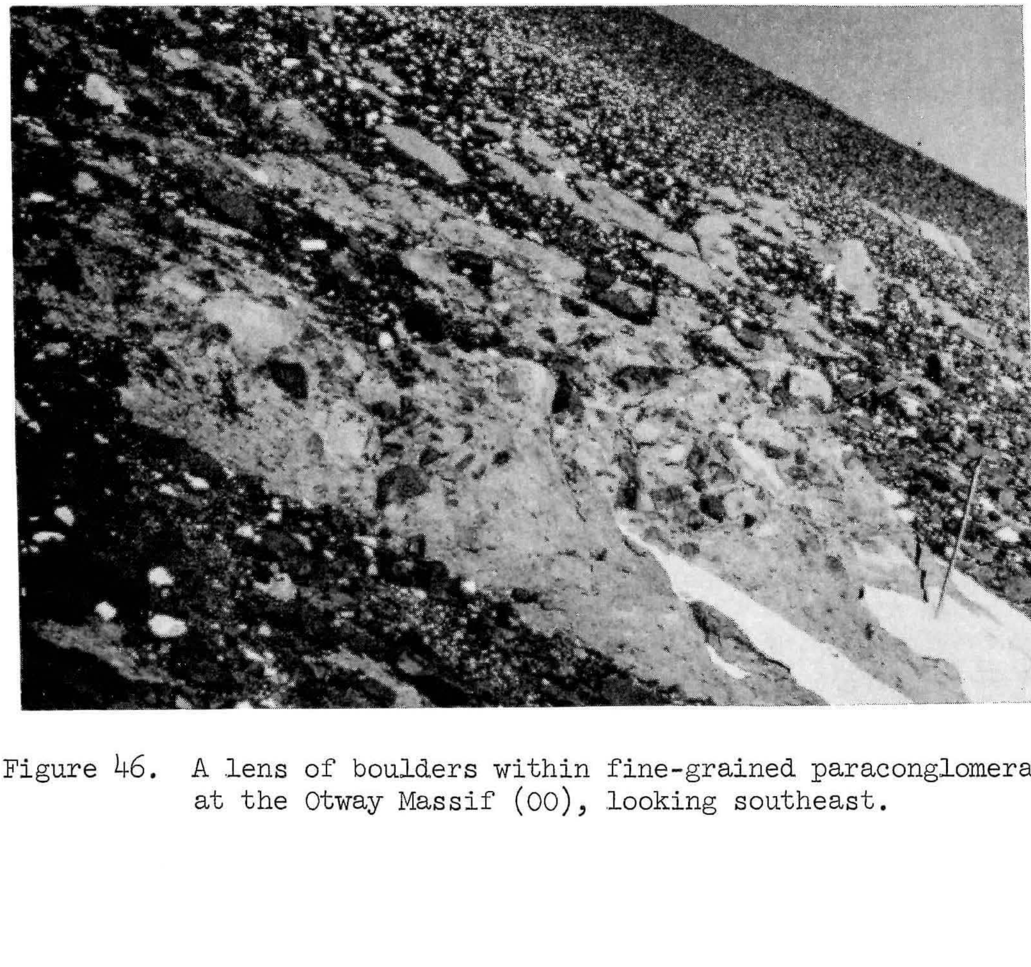


Figure 46. A lens of boulders within fine-grained paraconglomerate at the Otway Massif (OO), looking southeast.

Correlation and age

The only other unit described from the Transantarctic Mountains that is at all similar to the Prebble Formation is the Mawson Tillite of south Victoria Land, "a tough, compact, unsorted aggregate of rock fragments in a fine-grained matrix" (Warren, in Gunn and Warren, 1962). Volcanic material is common particularly in the upper part of that formation, and no undeniably glacial features have been found. Possibly the origin was similar to that proposed below for the Prebble Formation.

However, there are several differences between the Mawson Tillite and the Prebble Formation:

a. The Mawson Tillite rests on a surface with a least several hundred meters of relief cut in Beacon strata. There is no evidence of comparable relief at the base of the Prebble Formation.

b. The Prebble Formation has a smaller proportion and variety of non-volcanic clasts, is finer grained, and locally includes tuff beds.

c. Gunn (in Gunn and Warren, 1962) found two beds of Mawson Tillite within the basalt sequence at Carapace Nunatak in south Victoria Land, but no paraconglomerate beds have been found with the Kirkpatrick Basalt.

The age of the Prebble Formation is between that of the underlying Triassic Falla Formation and the overlying Lower to Middle Jurassic Kirkpatrick Basalt. There is no major break apparent in the sequence from the Dicroidium-bearing beds in the Falla Formation to the Prebble Formation on Mount Falla, and accretionary-lapilli tuff is found both in the upper part of the Falla Formation and the lower part of the Prebble Formation. However, Dr. D. H. Elliot has found blocks of vesicular basalt in paraconglomerate of the Prebble Formation in the Marshall Mountains, and blocks of basalt are quite common in parts of the Prebble Formation southeast of the Beardmore Glacier (p. 81).

The age of one such block (0003) from the Otway Massif was determined by the K-Ar whole rock method at Geochron Laboratories, Inc., (reference R-1172) to be 179 ± 10 million years. The sample was taken 120 m below the lowest Kirkpatrick Basalt flow, 120 m thick, from the boulder lens shown in Fig. 45. This is only slightly older than K-Ar ages obtained from basalt flows in the area (p. 86), and provides a lower age limit for the upper part of the Prebble Formation if the sample lost no argon during the extrusion of the overlying basalt flows.

Environment of deposition and source

Almost all of the material in the Prebble Formation is of volcanic origin, but non-volcanic processes may have played a considerable role in the deposition of much of the formation. Thin beds with shards or accretionary lapilli are probably purely pyroclastic, whereas agglomerate units, like those on Kenyon Peaks (T1) in which the matrix is finely vesicular, can be described, with some assurance, as autoclastic (Fisher, 1960). However, the origin of paraconglomerate is less certain. The poor sorting, massive appearance, and clastic nature of the rock preclude deposition by streams or lava flows. The vertical grading in the bed at Mount Pratt suggest pyroclastic or epiclastic processes. The lenticular grouping of large clasts within some paraconglomerate beds, and the non-volcanic nature of some of the clasts, suggest that these were not deposited directly as blankets of volcanic debris. The evidence favors, but by no means proves, a laharic origin for the paraconglomerate beds.

Fiske and others (1963) have described a similar though much thicker sequence of tuff breccias from the Ohanapecosh Formation, Mount Rainier National Park. The breccia units are massive, poorly sorted, have ill-defined vertical grading, and individual beds reach a maximum thickness of 110 m. Fiske and others proposed a subaqueous volcanic mudflow origin for those beds. However, the presence of accretionary lapilli and the lack of water-sorted material indicates deposition and burial of the Prebble Formation mainly on dry land. In some areas during deposition of the Prebble Formation tholeiitic flow rocks were being extruded and eroded, but most of the volcanic material in the formation is intermediate to acidic in composition, like that in the Buckley, Fremouw, and Falla Formations.

## Jurassic System - Ferrar Group

The name Ferrar Dolerites (Group) was proposed by Harrington (1958) for the tholeiitic rocks that intrude the Beacon strata of Victoria Land. Grindley (1963), in reporting the discovery of tholeiitic basalt flows above the Beacon sequence in the Beardmore Glacier area, included the basalts as a formation in the Ferrar Group.

### Ferrar Dolerite

In the Beardmore Glacier area, sheets of Ferrar Dolerite have an aggregate thickness of about 1000 m, compared with the 2500 m thickness of the intruded Beacon strata. The sills, which are by far the most common expression of the formation, normally range in thickness from 30 to about 200 m, though in the central Supporters Range a thickness of 600 m was estimated for one sill.

Most of the sills are between the top of the Pagoda Formation and the base of the Falla Formation. In most areas, but notably on the Tillite Glacier and around the Bowden Nevé, they appear to maintain the same stratigraphic position for many kilometers. In some areas, such as the Moore Mountains, Prebble Glacier, and the Supporters Range, inclined discordant sheets at least 100 m thick are also present. Dikes are not common and are normally only a few meters thick.

McDougall (1963) obtained three K-Ar ages from 147 to 155 million years for feldspar from samples of diabase from Clarkson Peak and Mount Markham in the northwestern part of the Beardmore Glacier area. Four K-Ar determinations for pyroxene from a diabase sample from the Roberts Massif at the head of the Shackleton Glacier ranged from 160 to 183 million years (Wade and others, 1965). Intrusion during the Jurassic is indicated.

## Kirkpatrick Basalt

The sequence of tholeiitic flows that cap the sedimentary and volcaniclastic section in the Queen Alexandra Range was named the Kirkpatrick Basalts by Grindley (1963). Grindley did not reach the Mount Kirkpatrick type section that he proposed, but measured a provisional type section on Blizzard Peak. Both sections, and many others have been visited by Dr. D. H. Elliot, who found no continuous sequence of lavas thicker than about 500 m in the Beardmore Glacier area (Elliot, in Barrett and others, 1967, 1968b). Individual flows range in thickness from 1.5 to 175 m; most have a thin amygdaloidal lower part and a thicker amygdaloidal upper part (ibid.). The large central part of some flows is a reddish-brown-weathering doleritic rock similar to that of the underlying sills; elsewhere the central part is a fine-grained basalt. Thin sedimentary beds between some flows have yielded conchostracans, ostracods, and fish and plant remains (Elliot and Tasch, 1967).

The age of the Kirkpatrick Basalt is Lower to Middle Jurassic (Kulp time-scale, 1961). A K-Ar age of 161 ± 3 million years was obtained from a basalt near the head of the Shackleton Glacier (Wade and others, 1965), but five K-Ar age determinations recently obtained by Elliot (in press) for basalt samples from the Beardmore Glacier area are slightly older; all but one, which has a similar age, are younger than the 179 million years reported above for the boulder from the underlying Prebble Formation.

## POST-PALEOZOIC FAULTING AND FOLDING

The marks of tectonism are not obvious in Beacon strata of the Beardmore Glacier area. In only two places have major faults or fault-related features been reported. McGregor (1965) noted a prominent scarp on the east side of the Dominion Range and suggested a fault origin for it. From McGregor's sections measured on each side of the scarp, the downthrow is estimated to be of the order of 600 to 1000 m to the east. Grindley and others (1965) noted the apparent stratigraphic displacement between the Shackleton Limestone of Buckley Island and the Triassic strata of the Dominion Range. Outcrops of Shackleton Limestone at an elevation of about 2400 m on the southern tip of Buckley Island (Young and Ryburn, 1968), and the observation by this writer, during a reconnaissance flight, of Fremouw strata on the northwest face of the Dominion Range at 2000 m suggests that the fault has downthrow to the west of the order of 1500 m.

The other area of obvious major faulting is the western margin of the Queen Elizabeth Range, where Laird and others (in preparation) have reported two major faults. Only one of these has any expression in the south Queen Elizabeth Range in the area covered by this study, and here the feature is largely monoclinal (Figs. 47, 48) with beds dipping as much as 50° to the west. The zone of maximum disturbance is about 300 m wide and can be followed from the Moore Mountains to Mount Weeks (Fig. 48) and Cranfield Peak. The displacement across the whole structure in the Moore Mountains is 350 m measured from the base of the Buckley Formation at A0 and at A1. To the north, Laird and others report a displacement of 800 m; to the south, the structure heads toward the low massif bounded by Sandford and Canopy Cliffs, but no displacement of sills or strata were seen there. The faulting is definitely post-Permian, but the movement appears both to be related to the Jurassic sill intrusion and to postdate it. The sill near the base of the Buckley Formation is folded and locally sheared, along with the rest of the strata, but the sill intruding the Mackellar Formation west of the fault is not present on the east side of the fault.

The structure contour map of the area (Fig. 49) is based on the elevation of the Fairchild-Buckley Formation contact because it is the most widespread readily identifiable horizon in the area. The map reveals a broad syncline plunging gently south-southeast on the west side of the Beardmore Glacier, but tending to curve west on the east side. A comparison of this map with both Permian and Triassic paleocurrent data (Fig. 4) suggests that the post-Beacon warping follows the trends of the Late Paleozoic and Early Mesozoic sedimentary basin.

In two parts of the Beardmore Glacier area toreva-block movement (Reiche, 1937) has resulted in large vertical displacements of Beacon strata in relatively recent times. The lesser of the two occurrences is on Solitary Peak (D1) about three quarters of the way up the north ridge. At this place a small diabase-capped knob of white sandstone

Figure 47. Looking north to Mount Angier from A0, Moore Mountains. The warping and faulting (downthrow to the west) are emphasized by the cliff-forming sill that can be traced across the photograph.

Figure 48. Monocline at C2 on Mount Weeks. Strata of the lower Buckley Formation are nearly horizontal at the right margin of the photograph but towards the center they dip at as much as 50° to the west. To the left the beds have begun to flatten out and dip at about 30°.

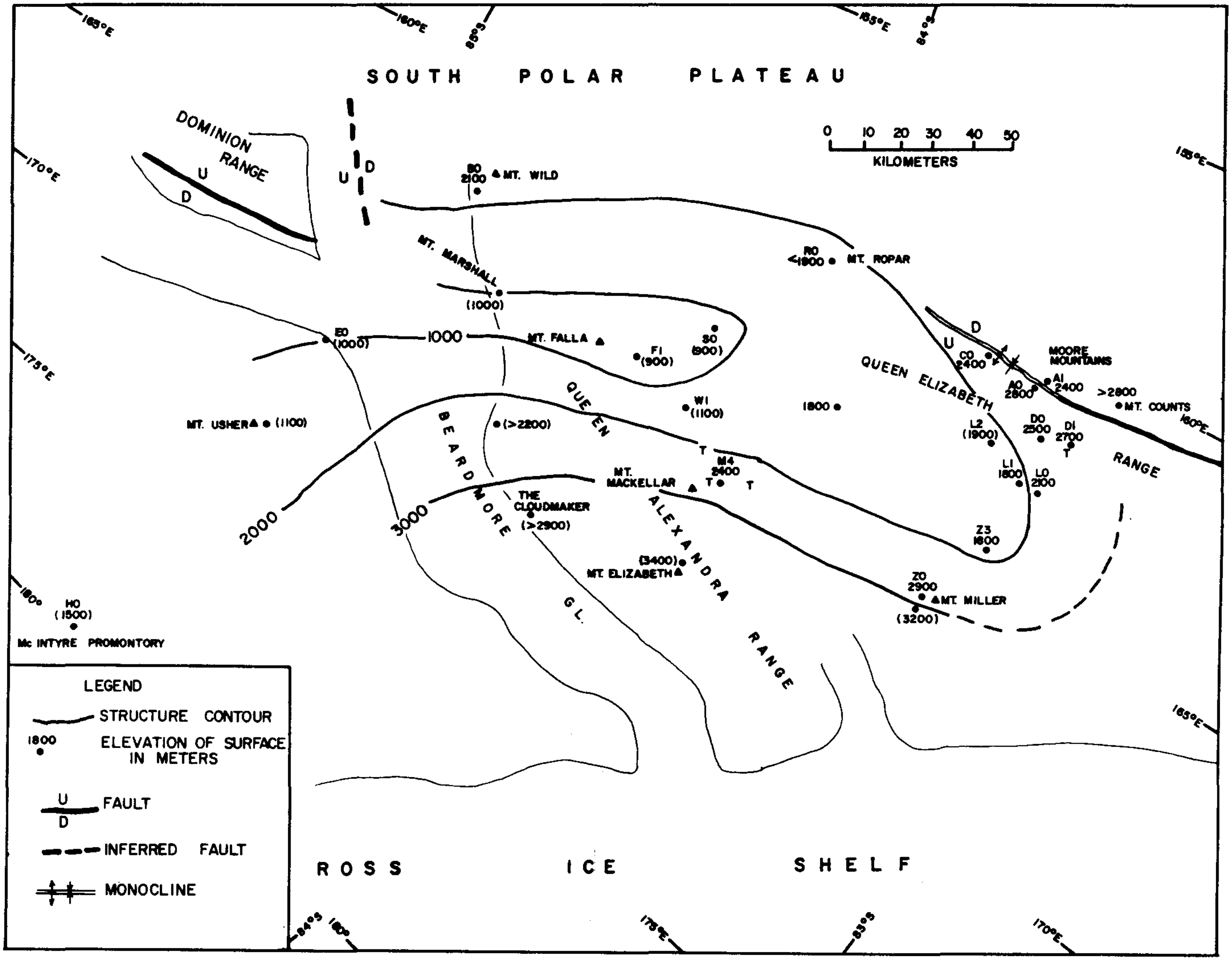



Figure 49. Structure contour map of the base of the Buckley Formation in the Beardmore Glacier area. Elevations in parentheses were based on the elevation of the top of the Buckley Formation or were estimated from the map in areas not visited. "T's" near Mount Mackellar and in the central Queen Elizabeth Range mark the location of toreva-blocks.

is separated from Mackellar siltstone by a brecciated zone a meter wide that is vertical on the up-ridge side of the knob and nearly horizontal on the down-ridge side. The block has dropped at least 200 m, because there are no diabase sills in the Solitary Peak section.

Several isolated toreva-blocks were found in the Mount Mackellar area (Fig. 49). Compacted but unlithified shale breccia with a diabase knob on top rests on an extensive sandstone platform 66 m above the base of the Buckley Formation at the top of a ridge 9 km northwest of Mount Mackellar. Closer to Mount Mackellar, two toreva-blocks, which include 100 and 220 m of strata from the Buckley and the lower part of the Fremouw Formation, have slid down at least 600 m, and possibly as much as 1400 m (Fig. 3, section M2). The massive quartzose sandstone beds in both blocks are identified as the lower part of the Fremouw Formation, because the Fremouw is the only part of the postglacial Beacon section that contains such quartzose sandstone. Sixteen kilometers northwest of Mount Mackellar a small nunatak 200 m lower than the brecciated shale mentioned above consists of coal measures (M5) that dip 45° to 70° easterly. Another isolated block was found on a ridge 10 km due west of Mount Mackellar. The sequence (W2) is 30 m thick and consists of diabase, sandstone, and coaly shale overlain by quartzose sandstone of the Fremouw Formation. The strata dip 60° southeast (Fig. 50). The shale beneath the orthoquartzite is intensely brecciated and, like the shale breccia described above, falls into its component fragments at the tap of a hammer.

A deep tectonic origin for the vertical displacements is discounted, because nowhere along the ridge between Mount Mackellar and Fairchild Peak is the Fairchild Formation displaced, and because the surface on which the movement took place is at least locally horizontal. The dips of several of the blocks, to the southwest, south, and southeast suggest that the blocks moved away from a massif situated near the present Mount Mackellar, possibly during the present geomorphic cycle. Diabase sills involved in the disruption indicate at least a post-Jurassic time of movement.

Figure 50. Massive quartzarenite at W2, 10 km west of Mount Mackellar. The ice axe rests against brecciated shale, on which the more competent strata are thought to have slid.

SUMMARY

The post-glacial Permian and Triassic Beacon sequence in the Beardmore Glacier area is about 2200 m thick and comprises six formations. The Mackellar, Fairchild and Buckley Formations are Permian, the Fremouw and Falla Formations are Triassic in age and the largely volcanic Prebble Formation is close to Triassic-Jurassic boundary. The Jurassic-Ferrar Group consists of an extrusive phase, the Kirkpatrick Basalt, and an intrusive phase, and the Ferrar Dolerite.

The Mackellar Formation, which conformably overlies glacial deposits of the Pagoda Formation (Permian), consists of about 90 m of laminated medium- to dark-gray shale and light-gray very-fine-grained sandstone in the type area near Mount Mackellar. To the northwest, however, the strata include more sandstone and become less carbonaceous; paleocurrent data indicate a source to the northwest. The Mackellar Formation was deposited in a quiet body of water that extended from the Queen Elizabeth Range at least to the Ohio Range, a distance of 1000 km; strontium 87/86 ratios suggest that the waters were nonmarine.

The Fairchild Formation is a massive arkosic sandstone, from 130 to 220 m thick. Strata in the Buckley Formation are crudely cyclic; sandstone beds with erosion surfaces at the base grade upward into finer-grained sandstone and carbonaceous shale. Coal beds were found at most localities, and form as much as six percent of the sedimentary section. Leaves (mainly Glossopteris), stems and logs are common, particularly in the upper part of the formation. The Buckley Formation was deposited on a flood plain of low gradient in a lower energy environment than that evisaged for the Fairchild Formation; the Buckley Formation has much more shale, and local current directions are far more variable. The source of the Buckley sand was threefold. Quartz plagioclase-K-feldspar sand, like that in the Fairchild Formation, came from the west; quartz-plagioclase sand was supplied from the north to the eastern part of the area, and intermediate to acid volcanic activity also poured detritus into the basin, overwhelming the nonvolcanic sand contribution in the upper part of the formation.

The Triassic Fremouw Formation, which is from 600 to 800 m thick, begins with a cyclic sequence about 100 m thick of quartzose sandstone and noncarbonaceous greenish-gray siltstone. Part of a labyrinthodont jawbone was discovered in the quartzose sandstone at Graphite Peak. Intermediate to acid volcanic material reappears in sandstone in the middle part of the formation, which is dominated by greenish-gray siltstone. Carbonaceous shale and logs and stems become common in the upper part of the formation. Root impressions occur throughout the formation. Leaves of Dicroidium were found in the upper part of the formation (and the lower part of the overlying Falla Formation).

The lower part of the Falla Formation is a cyclic sequence of sandstone and shale that in the type area is carbonaceous. The sandstone near the base of the formation is mucn more quartzose than the underlying Fremouw sandstone, but the quartz is diluted by volcanic material progressively up the section. The upper part of the formation is dominated by vitric tuff. The presence of accretionary lapilli suggests that at least one center of eruption lay within the present limits of the Queen Alexandra Range.

The two Triassic formations were deposited on a flood plain, like the Buckley Formation, but the sediment transport direction was to the west and northwest, and streams were much less sinuous.

The Falla Formation is overlain by the Prebble Formation, a Triassic?-Lower Jurassic unit that ranges in thickness from 0 to at least 460 m. The Prebble Formation consists of laharic deposits, agglomerate, tuff and tuffaceous sediment, and is overlain by the Lower to Middle Jurassic Kirkpatrick Basalt. The Beacon strata were intruded by Ferrar Dolerite about the same time as the basalts were extruded.

The intrusion of diabase sills has caused widespread metamorphism of some of the volcanic and calcareous sediments. Laumontite has replaced some volcanic and feldspar grains and matrix in sandstone from the Buckley and Fremouw Formations; in the Falla and Prebble Formations the replacement minerals are clinoptilolite, analcime and in two samples mordenite as well. Some albitization of plagioclase has occurred. A few sandstones from the Buckley and the lower part of the Fremouw Formation contain prehnite, and some near sills in the Buckley Formation include grossular garnet as well. Graphite was found in the Buckley Formation at three localities.

The Beardmore Glacier area has been gently warped about a northwest-southeast axis since the Jurassic Period. Major faulting seems to have been limited to two areas, the Dominion Range and the Queen Elizabeth Range. In the latter area, a normal fault passes southward into a monoclinal structure, which disappears farther south. Recent shallow tectonic activity is shown by toreva-blocks, involving as much as 220 m of the strata, that have slid down between 600 and 1400 m from a high area near the present Mount Mackellar.

# APPENDIX I - SELECTED STRATIGRAPHIC SECTIONS

This appendix contains the field description of each stratigraphic section that includes the type section of a formation defined or redefined in this report. The stratigraphic sections were measured by hand-leveling, and large thicknesses were checked by altimetry. The strata are described and the rock units numbered in ascending order. Column A contains the unit number, column B the thickness of each unit in meters, and column C the cumulative thickness. Latitude and longitude have been determined from map sheets of the U. S. Geological Survey's 1:250,000 reconnaissance series. Elevations determined by altimetry are given to the nearest 10 m and are followed by the identification alt. Elevations determined from the map sheets are given to the nearest 50 m and are followed by map est.

Each stratigraphic section is identified by a letter signifying the location of the area, and a digit identifying the section in that area. Rock samples are listed after the description of the bed from which they were taken, and their location is given in meters above the base of the unit. The two digit sample numbers increase going up the section. Thus each sample is individually identified by four characters, for example, F232 signifies Mt. Falla area, section 2, sample number 32.

Rock properties are described in the following order: lithology, color of unweathered surface, weathered color ("weathers" has been abbreviated to "w/"), grain size and then other relevant comments. The nature of the contact between units is described in the line between unit descriptions.

| A | | B | C |
|---|---|---|---|

Section M1. Base of middle buttress leading up to snow platform below west face of Mt. Mackellar.
Elevation at top of lower diabase sill about 2350 m (map est.).
Position 83° 56.6' S; 166° 29' E.

## Mackellar Formation

GLACIER ICE.

DIABASE SILL, 120 m thick.

| | | B | C |
|---|---|---|---|
| 1 | Shale, dark-gray.................................... | 3 | 3 |
| | - gradational contact - | | |
| 2 | Sandstone, light-gray (w/greenish gray or reddish), fine-grained, fissile, microcrosslaminated. White limestone beds up to 30 cm thick at 4, 6, and 9 m. Massive sandstone beds like unit 1 of the Fairchild Formation but 30 to 60 cm thick at 31 and 33 m....... | 34 | 37 |

Sample M101 21 m Fine ss.
Sample M102 30 m Fine ss.
Sample M103 31 m Fine to medium ss.

- gradational contact -

Thickness of Mackellar Formation.......................... 37 + m

## Fairchild Formation (Type Section)

| | | B | C |
|---|---|---|---|
| 1 | Sandstone, light-gray (w/light reddish brown), medium-grained, massive to thin-bedded. Stringers of gray (w/greenish gray) fissile very-fine sandstone 0.3 to 1 m thick at 2.4, 5, 7, 8, and 9 m. From 11 to 15 m about 20% of the sequence consists of white calcareous beds up to 60 cm thick. Shale fragments abundant at 37 m......................................... | 48 | 48 |

Sample M104 0.3 m Medium ss.
Sample M105 22 m Medium ss.
Sample M106 37 m Medium ss.

| | | B | C |
|---|---|---|---|
| 2 | Sandstone, light-gray (w/greenish gray), fine-grained, fissile.............................................. | 1.8 | 50 |
| | - gradational contact - | | |
| 3 | Shale, dark-gray. A few light-gray laminae. | 5 | 55 |
| | - erosion surface - | | |

| A | | B | C |
|---|---|---|---|
| 4 | Sandstone, white to light-gray, medium-grained, cross-bedded, massive. A few discoidal mudstone fragments up to 30 cm across in lower 8 m. Shale fragments at several levels.................................... | 70 | 125 |
| | Sample M107 1.8 m Ss.<br>Sample M108 42 m Ss.<br>Sample M109 65 m Ss.<br>- gradational contact - | | |
| 5 | Sandstone, light-gray (w/greenish gray), fine-grained, fissile................................................ | 7 | 131 |
| | - erosion surface - | | |
| 6 | Sandstone, light-gray, medium-grained, massive........ | 5 | 135 |
| | Sample M110 base Ss.<br>- gradational contact - | | |
| 7 | Sandstone, light-gray (w/greenish gray), fine-grained, microcrosslaminated. Dark shale becomes common in upper part............................................ | 12 | 147 |
| | Sample M111 2.7 m Ss.<br>- erosion surface - | | |
| | Thickness of Fairchild Formation.................... | 147 m | |

<u>Buckley Formation</u>

| A | | B | C |
|---|---|---|---|
| | - erosion surface - | | |
| 1 | Sandstone, very-light-gray, medium-grained, quartzose. A little quartz grit in lower 30 cm and lenses of quartz pebbles, mostly 1 cm with some up to 8 cm across, at 9, 11, and 13 m........................ | 18 | 18 |
| | Sample M112 0.9 m Ss.<br>Sample M113 9 m Ss.<br>Sample M114 10 m Ss.<br>- gradational contact - | | |
| 2 | Sandstone, light-gray (w/greenish gray), fine-grained, fissile................................................ | 3 | 21 |
| | - erosion surface - | | |
| 3 | Sandstone, white to light-gray, medium-grained, cross-bedded. Laminae and stringers up to 30 cm thick of light-gray fissile fine occur above 2 cm. Quartz pebbles in scattered lenses........................ | 6 | 27 |

| A | | B | C |
|---|---|---|---|
| | Sample M115 0.6 m Ss.<br>Sample M116 1.2 m Quartz pebbly ss.<br>- gradational contact - | | |
| 4 | Shale, dark-gray grading up into light-gray (w/greenish gray), microcrosslaminated......................... | 1.8 | 29 |
| | - erosion surface - | | |
| 5 | Sandstone, white to light-gray (w/greenish gray), medium-grained, with fine sandstone stringers....... | 0.9 | 30 |
| | - gradational contact - | | |
| 6 | Sandstone, light-gray (w/dark greenish gray), fine-grained, microcrosslaminated. Coarse sandy horizon at 3 m with quartz pebbles up to 8 cm across and one or two granitic and metasedimentary clasts. Quartz grit sprinkled through underlying bed of shaly sandstone............................................ | 10 | 40 |
| | Sample M116 2 m Limestone? from 15 cm lens<br>Sample M117 3 m Pebbly shaly ss.<br>-erosion surface - | | |
| 7 | Sandstone, light-gray, medium- to coarse-grained, quartzose, with green-gray laminae and stringers up to 30 cm thick................................................ | 7 | 47 |
| | Sample M118 0.6 m Ss.<br>- gradational contact - | | |
| 8 | Sandstone, light-gray (w/greenish gray), fine-grained, fissile................................................ | 2.1 | 49 |
| | DIABASE SILL, 100 m to highest point of sill. Joints indicate that upper surface dips to the southwest at 30°. | | |
| | Thickness of Buckley Formation........................ | 49 + m | |

Section BO. Base at ice level of Beardmore Glacier half way between Wild Icefalls and Lizard Point.
Elevation at base of section about 1850 m (map est.).
Position 84° 49.9' S; 163° 22' E.

A B C

Fairchild Formation

1 Sandstone, light-green-gray (w/same or light red brown), medium-grained, massive. Parallel bedding and some low-angle cross-bedding. Some laminae have abudnant muscovite and carbonaceous material finely disseminated or as small fragments. In the lower 24 m there are horizons every 3 m or discoidal dark shale fragments mostly 1 to 3 cm across and about 2 mm thick. At 4 m there are a few scattered pebbles less than 1 cm across. A gray chert pebble 14 cm across and a well-rounded quartz pebble 10 cm across were also found. The matrix at this level contains abundant red garnet. Dark-green medium-grained sandstone from 7 to 9 m. Scree from 25 to 60 m containing pieces of Shackleton limestone (common) and Pagoda tillite (rare) scattered among th dolerite blocks. From 139 to 146 m microcrosslaminated stringers of dark shale and fine sandstone up to 2 m thick are common. Above 119 m weathering has produced lapies. Broad scour surfaces up to 36 m across and 2 m deep also were found. They commonly contain fragments of fissile dark-gray fine-grained sandstone near the base. The upper 3 m of the unit shows some iron-staining........................................... 174 174

| | | |
|---|---|---|
| Sample B001 | 0.6 m | Ss. |
| Sample B002 | 24 m | Ss. |
| Sample B003 | 68 m | Ss. |
| Sample B004 | 85 m | Slightly calcareous ss. |
| Sample B005 | 107 m | Ss. |
| Sample B006 | 125 m | Ss. |
| Sample B007 | 150 m | Ss. |
| Sample B008 | 168 m | Ss. |
| Sample B009 | 173 m | Effloresence. |

- gradational contact -

2 Shale, black, coaly................................... 5 179

- slumped contact -

3 Sandstone, light- to medium-gray (w/white), fine- to medium-grained, massive. Iron-staining in upper 30 cm 6 185

- gradational contact -

4 Shale, black, coaly.................................. 4 189

- sharp contact -

5 Sandstone, light-gray (w/white), medium-grained, massive.. 4 193

Sample B010 0.6 m Ss.

| A | | B | C |
|---|---|---|---|
| 6 | Shale, black, coaly.................................. | 4 | 198 |
| 7 | Sandstone, light-gray (w/light yellow brown), medium-grained.............................................. | 1 | |
| | Shale, medium-gray to black, coaly in places........... | 8 | |
| | Sandstone, light-green-gray, medium-grained............ | 2.4 | |
| | NOTE: Moved 400 m south. Began measuring 14 m stratigraphically below the top of unit 6. | | |
| | Sandstone, light-gray, medium-grained.................. | | |
| | Shale, dark-gray, coaly in upper 3 m................... | 11 | |
| | - gradational contact - | | |
| | Sandstone, light- and dark-green gray, fine-grained, fissile............................................... | 3 | 198 |
| | - erosion surface - | | |
| | Thickness of Fairchild Formation....................... | 198 + m | |

<u>Buckley Formation</u> (Type Section)

| | | | |
|---|---|---|---|
| | - erosion surface - | | |
| 1 | Sandstone, light-gray (w/yellow brown and green gray), medium-grained, cross-bedded. Lenses of quartzose grit up to 30 cm thick containing pebbles up to 4 cm across at base. Red garnets abundant. Lenses of white quartzose sandstone in upper part of unit....... | 2.4 | 2 |
| | Sample B011 base Quartzose grit. | | |
| | Sample B012 0.6 m Ss. | | |
| | - gradational contact - | | |
| 2 | Sandstone, light-gray (w/white), medium- to coarse-grained, massive, cross-bedded. Laminae, stringers and clasts of green-gray fissile fine sandstone...... | 12 | 14 |
| | Sample B013 9 m Ss. | | |
| | - gradational contact - | | |
| 3 | Sandstone, light-green-gray (w/light and dark green gray) fine-grained, fissile, microcrosslaminated............ | 9 | 23 |
| | - sharp contact - | | |
| 4 | Sandstone, light-gray (w/white), medium- to coarse-grained, massive, cross-bedded. Green-gray fissile fine sandstone stringers and horizons of fine sandstone fragments......................................... | 22 | 45 |
| | Sample B014 11 m Ss. | | |

| A | | B | C |
|---|---|---|---|
| 5 | Shale, medium-gray (w/light and dark green gray), sandy.. | 2.4 | 47 |
| | - erosion surface - | | |
| 6 | Sandstone, very-light-gray (w/white), medium-to coarse-grained, massive, cross-bedded. Laminae and stringers of green-gray fissile fine sandstone. Lower 60 cm has lenses of quartz grit and weathers yellow-brown or green in patches. Medium-gray (w/light and dark green gray) sandy shale from 6 to 8 m. A lens of coaly shale from 13 to 15 m. The upper 60 cm of the unit is iron stained locally.................................... | 28 | 75 |
| | Sample B015 12 m Medium ss.<br>Sample B016 28 m Medium ss. | | |
| | - gradational contact - | | |
| 7 | Shale, black, coaly.................................... | 7 | 82 |
| | - sharp contact - | | |
| 8 | Sandstone, light-gray (w/green gray), medium-grained, massive. Iron-stained in lower 30 cm................ | 4 | 86 |
| 9 | Shale, black, coaly.................................... | 7 | 93 |
| | - slumped contact - | | |
| 10 | Sandstone, medium-gray (w/light gray), fine-grained, calcareous. Indistinct microcrosslamination.......... | 1.2 | 94 |
| | Sample B017 0.6 m Calcareous ss. | | |
| | - gradational contact - | | |
| 11 | Sandstone, light- to medium-gray (w/light and dark green gray), fine-grained, fissile, microcrosslaminated. Includes several lenses about 6 m across and 1 m thick of green and pink calcareous fine sandstone at 5, 7, and 10 m. Bedding runs from the adjacent sandstone into the lenses, but lower contacts are sharp and undulatory. Plant stems up to 60 cm long at 10 m..... | 12 | 106 |
| | Sample B018 7 m Calcareous fine ss. | | |
| | - gradational contact - | | |
| 12 | Shale, medium- to dark-gray (w/green gray or black), sandy. Coaly in a few patches........................ | 8 | 113 |
| | - gradational contact - | | |
| 13 | Sandstone, gray (w/yellow brown or green gray), fine- to medium-grained, fissile or flaggy. One or two thin coaly lenses.................................... | 5 | 119 |

| A | | B | C |
|---|---|---|---|
| 14 | SCREE.................................................. | 12 | 132 |

DIABASE SILL. Caps hills just west of Wild Icefalls.

Section B1. 2 km east-southeast of Mt. Wild. A melange of between 45 and 75 m of medium-gray baked shale and fine sandstone between two diabase sills each about 120 m thick. The lower sill is that which overlies section BO. About 3 m of graphite were found 6 m below the upper sill. Thinner beds of graphite were found 6 m below the upper sill. Thinner beds of graphite occur farther down. Only a few beds can be traced for more than about 6 m because of the extensive disruption associated with diabase intrusion.

Elevation about 2650 m (map est.).
Position 84° 48.5' S; 162° 55' E.

Sample B100 15 m Sediment clasts in dolerite groundmass.
Sample B101 -24 m Graphite.
Sample B102 - 6 m Fine ss.

Section B2. From base of southeast ridge of Mt. Wild to the summit. Section begins at top of sill that overlies B1. The cumulative thickness of the Buckley Formation to this level is thought to be about 210 m

Elevation at base of section is 2660 m (alt.).
Position 84° 48.0' S; 162° 45' E.

Buckley Formation

| | | | |
|---|---|---|---|
| 1 | Sandstone, very-light-gray (w/light gray or light pink gray), medium-grained, massive, cross-bedded......... | 8 | 8 |

Sample B200 3 m Ss.
- sharp contact -

| | | | |
|---|---|---|---|
| 2 | Siltstone, light- to medium-gray (w/white), shaly in upper 2 m. Glossopteris.............................. | 4 | 13 |

- slumped contact -

| | | | |
|---|---|---|---|
| 3 | Sandstone, light-pink-gray (w/same), medium-grained, massive.............................................. | 10 | 23 |

| A | | B | C |
|---|---|---|---|
| | Sample B201 1 m Ss. | | |
| | - sharp contact - | | |
| 4 | Siltstone, medium-gray (w/white). A few thin interbeds of medium sandstone.................................... | 2.1 | 25 |
| | - erosion surface - | | |
| 5 | Sandstone, light-gray (w/same), medium-grained, massive. Lens of white siltstone fragments up to 30 cm across in lower 1.5 m. Light- to medium-gray shale fragments up to 10 cm thick and 60 cm across common at 8 and 10 m. Above 20 m fine sandstone beds appear and become common............................................... | 28 | 53 |
| | Sample B202 11 m Ss.<br>Sample B203 24 m Ss. | | |
| 6 | Shale, medium- to dark-gray (w/light gray). Coal from 1 to 2 m.................................................. | 3 | 56 |
| | - gradational contact | | |
| 7 | Coal, with a few beds 8 to 16 cm thick of dark-gray shale. Diabase 30 cm thick at 4 m........................... | 8 | 64 |
| | - gradational contact - | | |
| 8 | Shale, dark-gray (w/light to medium gray)............. | 9 | 74 |
| | - gradational contact - | | |
| 9 | Sandstone, medium-gray (w/very light gray), fine-grained, massive, with several medium sandstone and light-gray shale beds about 30 cm thick......................... | 7 | 81 |
| | - sharp contact - | | |
| 10 | Sandstone, light-gray, fine-grained. Slump-folded....... | 0.3 | 81 |
| 11 | Siltstone, light- to medium-gray (w/white or light pink gray), thick-bedded, vertical joints in places. Some beds laminated and quite fissile. A few stems 2 to 8 cm across. Glossopteris at 12 m. A few short trails about 1 mm across............................. | 18 | 100 |
| | Sample B205 0.6 m Very fine ss.<br>Sample B206 12 m Siltstone. | | |
| | Summit of Mt. Wild | | |
| | Thickness of Buckley Formation (sections B0, B1 and B2). | 310 + m | |

Section FO. From the foot of south-facing slopes of Fremouw Peak to the summit.
Elevation at base of section is 2020 m (alt.).
Position 84° 17.8' S; 164° 07' E.

<u>Fremouw Formation</u> (Type Section)

| A | | B | C |
|---|---|---|---|
| | DIABASE SILL. At least 10 m thick. | | |
| 1 | Sandstone, light-gray (w/pink), medium- to coarse-grained, massive, cross-bedded. A few mudstone fragments to 18 cm across, and small rounded quartz pebbles. Spotty appearance | 1.8 | 2 |
| | Sample FO01 1.2 m Coarse ss. | | |
| 2 | Sandstone, green-gray, fine-grained, fissile | 1.8 | 4 |
| | Sample FO02 0.6 m Fine ss. | | |
| 3 | Sandstone, light-gray, medium- to coarse-grained, massive. Layer of sub-rounded, distorted mudstone fragments at 2 m | 2.1 | 6 |
| 4 | Sandstone, green-gray, fine-grained, fissile | 1.5 | 7 |
| | - erosion surface - | | |
| 5 | Sandstone, light-gray, medium- to coarse-grained, massive. Solemarks at base. Cross-bedded. Mudstone fragments up to 8 cm across in lower 30 m. Small quartz pebbles and grit scattered throughout unit | 6 | 13 |
| | Sample FO03 base Erosion surface and overlying ss. | | |
| 6 | Sandstone, light-gray, medium- to coarse-grained, fissile, poorly cemented, with a few fissile, fine sandstone stringers | 4 | 17 |
| | Sample FO04 3 m Medium ss. | | |
| 7 | Sandstone, light-gray, medium- to coarse-grained, massive massive | 7 | 24 |
| 8 | Sandstone, green-gray, fine-grained, fissile | 17 | 41 |
| | Moved 150 m east | | |
| | - erosion surface - | | |

| A | | B | C |
|---|---|---|---|
| 9 | Sandstone, light-gray, medium- to coarse-grained, massive, cross-bedded. Lower 0.3 to 1 m contains abundant spheroidal and tabular mudstone fragments up to 30 cm across. A few small quartz pebbles. Unit becomes finer towards top, and includes several green, fissile, fine sandstone stringers up to 30 cm thick, one of which was boudinaged, presumably during the emplacement of the overlying cross-bedded sandstone........................................... | 6 | 47 |
| | Sample F009 1.2 m Ss. | | |
| | - gradational contact - | | |
| 10 | Shale, light-green-gray, interbedded with subdominant microcrosslaminated fine-grained sandstone. Units up to 1 m thick..................................... | 10 | 57 |
| | Sample F010 0.6 m Shale.<br>Sample F011 5 m Fine ss. | | |
| | - erosion surface - | | |
| 11 | Sandstone, white, coarse-grained, interbedded with light-green-gray fine sandstone which dominates in the upper 2 m. Rounded, tabular mudstone fragments up to 15 cm across, and quartz pebbles up to 5 cm across, occur in discontinuous lenses from 0 to 0.6 m and from 1.2 to 1.5 m............................................ | 5 | 62 |
| | - gradational contact - | | |
| 12 | Shale, light-green-gray................................ | 5 | 67 |
| | - contact obscured - | | |
| 13 | Sandstone, light-green-gray, medium-grained, poorly sorted, cross-bedded, with scattered quartz pebbles and grit. At 2 m it grades up into shale which is separated from the sandstone above by an undulating sharp contact. Mudstone fragments to 5 cm across from 2.7 to 3.3 m. Upper 2 m is better sorted........ | 5 | 72 |
| | - gradational contact - | | |
| 14 | Shale, light-green-gray................................ | 3 | 76 |
| | - contact obscured - | | |
| 15 | Sandstone, light-gray, medium-grained poorly sorted, cross-bedded. Scattered small quartz pebbles......... | 2.1 | 78 |

| A | | B | C |
|---|---|---|---|
| | DIABASE SILL. 2 m. | | |
| 15 | Sandstone; like unit 14................................ | 1.2 | 79 |
| | - gradational contact - | | |
| 16 | Shale, light-green-gray. From 2.1 to 2.7 m there is a green-gray calcareous mudstone with mudcracks about 15 cm across on the upper surface.................... | 9 | 88 |
| | Sample BF012 2.4 m Calcareous mudst. | | |
| | - gradational contact - | | |
| 17 | Shale, light-green-gray, with subordinate light-green-gray, fine-grained sandstone beds 0.3 to 1 m thick, and lens over 15 m or so. Some sandstones have white spidery threads. Mud fragment horizon at 10 m....... | 11 | 99 |
| | Sample F013 1.8 m Fine ss | | |
| | - sharp contact - | | |
| 18 | Sandstone, light-gray and green-gray, fine-to medium-grained. Distinct dark-green laminae and shale stringers. Microcrosslaminae and crossbeds. Thin mudstone fragment concentrations and scattered fragments throughout.................................... | 15 | 114 |
| | Sample F014 0.6 m Light-gray ss.<br>Sample F016 15 m Quartzose ss. | | |
| | - gradational contact - | | |
| 19 | Shale, green,sandy.................................... | 6 | 120 |
| | DOLERITE, discordant.' | | |
| | Walked along bedding for about 1.6 km to the east, but exposure was poor, and correlation may be off by as much as 15 m. | | |
| 20 | Sandstone, light-green-gray, fine-grained blocky. Subordinate 30 to 60 cm beds of light-green-gray mudstone. Lenses of light-gray, medium sandstone with sharp lower contact, mudstone fragments up to 10 cm across, and a gradational upper contact occur at 11 to 12 m, 15 to 16 m, 19 to 20 m, 21 to 22 m, 35 to 37 m, 42 to 45 m, 57 to 59 m (contains brown discoidal concretions up to 60 cm across), 62 to 63 m. A dark gray coloration in mudstone in the upper 12 m as patches several feet across and as coarse laminae.... | 80 | 201 |

| A | | B | C |
|---|---|---|---|
| | Sample F017 0.6 m White ss.<br>Sample F018 1.2 m Green-gray fine ss.<br>Sample F019 1.8 m Green-gray mudst.<br>Sample F020 36 m Ss with lower contact of unit.<br>Sample F021 58 m Concretion.<br>- sharp contact - | | |
| 21 | Sandstone, finely mottled pink and green, medium-grained, cross-bedded. Abundant mudstone fragments............ | 2.1 | 203 |
| | - gradational contact - | | |
| 22 | Mudstone, green-gray, with a few coal streaks........... | 6 | 209 |
| | - sharp contact - | | |
| 23 | Sandstone, light-pink, medium- to coarse-grained. A few small mudstone fragments near base, and coal fragments up to 20 cm across. Laminae and stringers up to 30 cm thick of green fine sandstone.................. | 3 | 212 |
| 24 | Mudstone, green-gray, with occasional sandy layers 30 to 60 cm thick. A few dark-gray patches and horizons of white flecks......................................... | 3 | 215 |
| 25 | Sandstone; like unit 23................................ | 1.8 | 217 |
| 26 | Mudstone, green-gray.................................... | 0.6 | 218 |
| 27 | Sandstone; like unit 23................................ | 1.5 | 220 |
| 28 | Mudstone, green-gray.................................... | 13 | 232 |
| 29 | Sandstone; like unit 23................................ | 3 | 235 |
| 30 | Mudstone, green-gray.................................... | 11 | 246 |
| | - erosion surface - | | |
| 31 | Sandstone, light-gray, medium- to coarse-grained, cross-bedded. Common laminae and stringers of green fine sandstone. Ovoid and discoid mudstone fragments up to 10 cm across are scattered throughout, but are common in the lower 30 cm and from 1.8 to 2.1 m, where there are also a few quartz pebbles up to 2 cm across. Coal streaks and fragments are also common. Subrounded to well-rounded pebbles up to 12 cm across occur at several levels from 4 to 9 m. Lithologies include acid volcanic, argillite, conglomerate, vein quartz........................................ | 11 | 257 |

| A | | B | C |
|---|---|---|---|
| | Sample F024 0.4 m Ss.<br>Sample F025 4 to 9 m Pebbles.<br>Sample F026 10 m Ss.<br>- gradational contact - | | |
| 32 | Sandstone, light-green-gray, fine- to medium-grained, with about 6 thin layers of shale pebble conglomerate. Coaly laminae and fragments. Pebbles ovoid and tabular........................................ | 1.8 | 258 |
| | Sample F027 1.5 m Shale pebble conglomerate.<br>- gradational contact - | | |
| 33 | Mudstone, light-green-gray. 60 cm sandstone lens at 10 m. Upper 1.2 m of unit; overlying sandy shale<br>light-gray clay 1 cm smooth<br>light-green-gray clay 5 cm surfaces<br>light-gray clay 1 cm<br>pitted light-green-gray clay 10 cm with roots.<br>light-green-gray mudstone 20 cm<br>light-green-gray fine sandstone 12 cm................ | 15 | 273 |
| 34 | Shale, light-green-gray, sandy. Upper 60 cm has root-holes................................................<br>- sharp contact - | 1.2 | 274 |
| 35 | Sandstone, light-pink, medium- to coarse-grained........<br>- gradational contact - | 1.8 | 276 |
| 36 | Mudstone, light-green-gray. White flecks. A few layers with abundant plant fragments........................<br>- sharp contact - | 4 | 280 |
| 37 | Sandstone; like unit 35................................<br>- gradational contact - | 2.4 | 283 |
| 37 | Mudstone, light-green-gray. Rootholes from 2.7 to 3.3 m.<br>- erosion surface - | 11 | 294 |
| 39 | Sandstone, white to light-gray, very-coarse-grained, quartzose, cross-bedded. The basal 0.3 to 1.5 m is a lens of much less quartzose, medium sandstone. The upper surface of this contains "crag and tail" that look as if they were once part of a stream bed protected from the current by a boulder on top. Garnet abundant for a meter or more above this surface. A few microcrosslaminated stringers of green, fine sandstone near the top of the unit.............. | 19 | 313 |

| A | | B | C |
|---|---|---|---|
| | Sample F029 0.9 m Medium ss.<br>Sample F030 1.2 m Base of quartzose ss.<br>Sample F031 5 m Quartzose ss.<br>Sample F032 17 m Quartzose ss.<br>- gradational contact - | | |
| 40 | Mudstone, green-gray. A few rootholes in upper 0.6 m...<br>- erosion surface - | 3 | 316 |
| 41 | Sandstone, white to light-gray, very-coarse-grained, cross-bedded. Quartz pebbles and abundant garnet in lower 1 m. Lower surface is dotted with well-defined pits about 0.3 cm across..................... | 8 | 324 |
| | Sample F033 base Erosion surface.<br>- gradational contact - | | |
| 42 | Sandstone, light-gray, fine-grained. A few green-gray mudstone layers. Some microcrosslamination...........<br>- erosion surface - | 23 | 347 |
| 43 | Sandstone, very-light-gray, medium-grained, cross-bedded. Some green laminae. Discoidal mudstone fragments up to 5 cm across in lower 30 cm. A few coal streaks. Sand wave preserved.........................<br>- gradational contact - | 2.4 | 350 |
| 44 | Sandstone, green-gray, very-fine-grained. White flecks and bits of roots. A few carbonaceous layers.........<br>- erosion surface - | 4 | 353 |
| 45 | Sandstone, very-light-gray, medium-grained. A few small mudstone fragments................................... | 4 | 356 |
| | Sample F034 0.3 m Ss.<br>- gradational contact - | | |
| 46 | Mudstone, green-gray....................................<br>- erosion surface - | 3 | 359 |
| 47 | Sandstone, light-gray, medium-grained. A few coal streaks and rare mudstone fragments in lower 60 cm. A few brown discoidal concretions..................... | 5 | 364 |
| | Sample F036 1.5 m Brown concretion.<br>- gradational contact - | | |

A B C

48 Mudstone, light-green-gray, with subequal light-green-gray, fine-grained sandstone, in 60 cm beds.
4 to 5 m Hard, pitted mudstone.
11 to 12 m Lens of white medium sandstone............. 15 379

49 Sandstone, white to light-gray, medium-grained, massive, cross-bedded. A few carbonaceous and green-gray laminae. Fine sandstone stringers. Brown discoidal concretions from 3 to 60 cm across. Discoidal mudstone fragments up to 30 cm across and up to 10 cm thick common at 8 and 10 m............................ 23 402

Sample F037 7 m Ss.
Sample F038 21 m Ss.
- gradational contact -

50 Sandstone, green-gray, fine-grained...................... 2.7 405
- erosion surface -

51 Sandstone, light-gray, medium-grained, cross-bedded Abundant small mudstone fragments in lower 1 m. Green-gray laminae. Brown concretions....................... 1.8 407
- snow contact -

52 Shale, dark-gray, with striated stem fragments............ 4 411
- erosion surface -

53 Sandstone, white, medium-grained, cross-bedded. Common green-gray laminae. Bands of small mudstone fragments about 1 cm across between 10 and 12 m.................. 12 423

Sample F039 11 m Ss.
- gradational contact -

Sandstone, green-gray, fine-grained.................... 1.8
- gradational contact -

Mudstone, green-gray, with white flecks................ 1.8

DIABASE SHEET, discordant. Section continued on other side of intrusion. Equivalent beds are indicated by unit number.

49 Sandstone, light-gray, medium-grained, cross-bedded. Brown concretions up to 60 cm across. Mudstone fragments up to 30 cm across and 8 cm thick are common from 7 to 8 m............................................. 17

Sample F040 12 m Ss.
- gradational contact -

| A | | B | C |
|---|---|---|---|
| | Mudstone, green-gray, interbedded with green-gray fine sandstone........................................ | 5 | |
| | - erosion surface - | | |
| | Sandstone, light-gray, medium-grained.................... | 1.5 | |
| | - gradational contact - | | |
| | Mudstone, green-gray................................... | 2.1 | |
| | - erosion surface - | | |
| 53 | Sandstone, white (pinkish above 6 m), medium-grained, cross-bedded. Green-gray laminae and stringers. Brown concretions about 8 cm across. Mudstone fragments in lower 30 cm, at 5 m (up to 50 cm across), and from 10 to 11 m (about 1 cm across).................... | 11 | |
| | DIABASE SILL 1 m thick at 0.5 m. | | |
| | - gradational contact - | | |
| 54 | Sandstone, light-green-gray, fine-grained, laminated. A few thin mudstone beds. Upper 60 cm is mudstone with rootholes............................................... | 4 | 427 |
| | - erosion surface - | | |
| 55 | Sandstone, light-pink-gray (w/red brown), medium-grained, cross-bedded............................................ | 2.4 | 429 |
| | Sample F041 0.3 m Ss. | | |
| | - gradational contact - | | |
| 56 | Mudstone, green-gray, interbedded with green-gray fine sandstone. A few concretionary lenses of limestone up to 15 cm thick. Laminae appear to cross them. Beds of pinkish white medium sandstone up to 1.2 m thick are scattered throughout, but dominate from 6 to 15 m. Abundant rootholes occur in green-gray mudstone from 32 to 33 m and at 41 m. <u>Neocalamites</u> (?).............. | 42 | 471 |
| | Sample F042 5 m Fine ss.<br>Sample F043 15 m Mudst.<br>Sample F044 16 m Ss.<br>Sample F044A 40 m Mudstone with <u>Neocalamites</u>(?) | | |
| | - erosion surface - | | |
| 57 | Sandstone, white to pink, medium-grained, cross-bedded. Mudstone fragments up to 3 cm across in lower 30 cm. Coal streaks at 1.2 m................................. | 5 | 476 |
| | Sample F045 2.1 m Ss. | | |
| | - gradational contact - | | |

| A | | B | C |
|---|---|---|---|
| 58 | Sandstone, white to pink, medium-grained, with beds of green-gray fine sandstone and mudstone common. Root-holes in mudstone from 8 to 9 m. Stems common at several levels.................................... | 20 | 496 |
| 59 | Sandstone, light-pink-gray, medium-grained cross-bedded.. | 2.1 | 498 |
| | Sample F046 1.2 m Ss. | | |
| | - gradational contact - | | |
| 60 | Mudstone, green-gray.................................... | 2.4 | 501 |
| | - erosion surface - | | |
| 61 | Sandstone, white, medium-grained. Abundant mudstone fragments 1 cm across in lower 30 cm.................. | 1.8 | 503 |
| | DIABASE DIKE. Traversed east for 60 m. | | |
| 62 | SCREE.................................................. | 7 | 510 |
| 63 | Mudstone, green-gray, sandy. Rootholes.................. | 0.6 | 511 |
| | - erosion surface - | | |
| 64 | Sandstone, light-gray, medium-grained. A few mudstone fragments and coal streaks in lower 30 cm............. | 8 | 518 |
| | Sample F047 base Ss. | | |
| | - gradational contact - | | |
| 65 | Mudstone, green-gray.................................... | 1.8 | 520 |
| | - erosion surface - | | |
| 66 | Sandstone, light-gray, medium-grained, massive. Mudstone and fine sandstone fragments up to 30 cm across but mainly only 2 or 3 cm across, are common in the lower 1.2 m, at 5m, 7 to 8 m, 9 to 10 m, 11 m and 14 m. Most fragments are discoidal but some are tabular and spherical. Flattened stem impressions from 10 to 60 cm across are commonly associated with the fragment concentrations. Above 5 m most stems have been silicified. From about 12 to 18 m knobbly spheroidal concentrations 2 to 5 cm across are common.................................... | 41 | 561 |
| | Sample F048 3 m Pink and green ss. | | |
| | Sample F049 10 m Ss. | | |
| | Sample F050 14 m Concretion. | | |
| | Sample F051 15 m Silicified wood. | | |
| | Sample F052 29 m Ss. | | |
| | Sample F053 41 m Ss. | | |
| | - sharp contact - | | |

| A | | B | C |
|---|---|---|---|
| 67 | Sandstone, medium-gray, medium-grained, cross-bedded. Abundant carbonaceous laminae and coaly lenses up to about 30 cm thick. Mudstone fragments up to 15 cm across, but mostly about 2 cm, are common. The fragments occur mainly as thin concretions usually above but occasionally below the coaly lenses. At least one limestone lens 20 cm thick and 60 cm across... | 17 | 578 |
| | Sample F054 14 m Gray ss.<br>Sample F055 15 m Limestone lens.<br>- erosion surface - | | |
| 68 | Sandstone, light-gray (w/red brown), medium-grained. Mudstone fragments up to 30 cm across abundant from 0 to 0.6 m and from 1.8 to 2.1 m. Siliceous veins and wisps in lower and upper 1 m. Log exposed in cross-section at 1.2 m................................ | 9 | 587 |
| | Sample F056 0.6 m Ss.<br>Sample F057 1.2 m From log (radius 65 cm) 28 cm from center.<br>Sample F058 5 m Section of log about 20 cm across.<br>Sample F059 6 m Ss. | | |
| 69 | Sandstone, light-green-gray, fine-grained laminated, with disrupted, silicified? woody laminae in lower 30 cm....<br>- gradational contact - | 0.9 | 588 |
| 70 | Mudstone, light-brown-gray. One or two fine sandstone beds..............................................<br>- erosion surface - | 10 | 598 |
| 71 | Sandstone, light-gray, medium-grained. Spheroidal and discoidal mudstone fragments about 1 cm across occur in scattered lenses. A few impressions about 30 cm across of flattened logs.................................. | 4 | 603 |
| | DIABASE SILL. 12 m thick. | | |
| 72 | Coal. Partly coked..................................<br>- gradational contact - | 2.4 | 605 |
| 73 | Mudstone, medium-gray (w/white), sandy, with several beds about 30 cm thick of carbonaceous fine sandstone...... | 9 | 614 |
| | Sample F061 7 m Fine ss.<br>- sharp contact - | | |
| | Thickness of Fremouw Formation.......................... | 614 + m | |

| A | | B | C |
|---|---|---|---|
| | **Falla Formation** | | |
| 1 | Sandstone, very-light-gray (w/light red brown), medium-grained, massive. Some 0.6 to 2 m beds of fine sandstone. Several surfaces (erosion? surfaces) within the unit, and one has plant stem impressions. From 6 to 12 m there are several lenses less than 1 m thick of medium-gray mudstone; the sandstone in this interval is rather knobbly. | 27 | 27 |
| | Sample F062 1.8 m Fine ss.<br>Sample F063 2.1 m Medium ss.<br>Sample F064 14 m Knobbly ss.<br>- gradational contact - | | |
| 2 | Sandstone, medium-gray, fine-grained, microcrosslaminated. | 2.4 | 30 |
| | - gradational contact - | | |
| 3 | Mudstone, medium-gray, with 15 to 30 cm beds of microcrosslaminated gray fine sandstone. | 30 | 59 |
| | 5 to 6 m Coaly shale<br>6 to 7 m Light-gray (w/red brown), medium ss.<br>23 to 24 m Light-gray (w/red brown), medium ss.<br>- erosion surface - | | |
| 4 | Sandstone, light-gray (w/red brown), medium-grained, knobbly, vaguely cross-bedded. | 1.8 | 61 |
| | Sample F066 0.6 m Medium ss. | | |
| 5 | Shale, black, coaly. | 0.6 | 62 |
| 6 | Mudstone, medium-gray. | 4 | 65 |
| | - erosion surface - | | |
| 7 | Sandstone, light-gray (w/red brown), medium grained, knobbly, vaguely cross-bedded. | 9 | 74 |
| | DIABASE SILL. 24 m thick. | | |
| 8 | Mudstone, light-gray. A few fine and medium sandstone beds up to 60 cm thick. | 10 | 84 |
| | Sample F065 9 m Mudstone with *Dicroidium*.<br>- sharp contact - | | |

| A | | B | C |
|---|---|---|---|
| 9 | Sandstone, light-gray (w/red brown), medium-grained. Mudstone fragments about 1 cm across at 1 m............ | 1.8 | 86 |
| | Sample F067 1 m Ss. | | |
| | Thickness of Falla Formation............................ | 86 + m | |
| | DIABASE to top of Mt. Fremouw (about 120 m to northeast). | | |

Section F2. Rocky, north-facing slope leading onto the west ridge of Mr. Falla.
Elevation at base of section is 2610 m (alt.).
Position 84° 21.0' S; 164° 42' E.

<u>Falla Formation</u> (Type Section)

| A | | B | C |
|---|---|---|---|
| | SNOW. | | |
| 1 | Sandstone, light-gray (w/red brown), medium- to coarse-grained, cross-bedded, massive........................ | 8 | 8 |
| | Sample F201 1.2 m Ss. | | |
| | - gradational contact - | | |
| 2 | Sandstone, light-gray, fine-grained, microcrosslaminated. | 0.9 | 9 |
| | Sample F202 0.3 m Fine ss. | | |
| | - gradational contact - | | |
| 3 | Shale, medium- to dark-gray, sandy. Lenses of fine sandstone from +4 to +5 m and from +5 to +6 m. Abundant small carbonaceous fragments. One or two coaly horizons............................................ | 16 | 25 |
| | Sample F203 6 m Green-gray fine ss. | | |
| | Sample F204 7 m Dark-brown fine ss. | | |
| | Sample F205 9 m Shale | | |
| | - gradational contact - | | |
| 4 | Sandstone, light-green-gray, fine-grained, microcross-laminated and cross-bedded............................ | 4 | 29 |
| | - gradational contact - | | |
| 5 | Shale, green-gray, coaly in middle 0.9 m................ | 1.8 | 31 |
| | - gradational contact - | | |
| 6 | Sandstone, light-green-gray, fine-grained............... | 0.9 | 32 |
| | - gradational contact - | | |

| A | | B | C |
|---|---|---|---|
| 7 | Shale, medium- to dark-gray. Coaly at least from 0.6 to 1.2 m. 2.4 to 3 m, and from 18 to 20 m................ | 22 | 54 |
| | Sample F206 21 m Shale. | | |
| | - erosion surface - | | |
| 8 | Sandstone, light-gray (w/red brown), coarse-grained. Conglomerate of quartz pebbles up to 2 cm across in lower 1.5 m................................................ | 4 | 58 |
| | Sample F207 0.3 m Conglomerate. | | |
| | Sample F208 3 m Coarse ss. | | |
| | - gradational contact - | | |
| 9 | Sandstone, green-gray, fine-grained, fissile. Some thin coaly layers, and shaly coarse sandy lenses............ | 20 | 78 |
| | Sample F209 0.6 m Ss. | | |
| | Sample F210 0.9 m Ss. | | |
| | - erosion surface - | | |
| 10 | Sandstone, white to light-gray (w/red brown), medium-grained, cross-bedded. A few shale fragments in lower 30 cm................................................ | 4 | 83 |
| 11 | Sample F211 2.4 m Light-gray ss. | | |
| 11 | Shale, dark-gray, in 1.2 to 2.4 m beds, interbedded with 0.6 to 0.9 m beds of light-gray shaly fine to medium sandstone. Several coaly horizons near the top, as well as coaly laminae in the sandstone.................. | 27 | 110 |
| 12 | SNOW.................................................. | 5 | 115 |
| | - erosion surface - | | |
| 13 | Sandstone, white to light-gray (w/red brown), medium- to coarse-grained Shale fragments throughout lower 4 m, but are concentrated from 0.6 to 1.2 m and at 4 m. Mainly rounded thin discs up to 35 cm across. Abundant coal streaks. Rare quartz pebbles..................... | 20 | 135 |
| | Sample F212 1.2 m Ss and shale fragments. | | |
| | Sample F213 9 m Ss. | | |
| | - gradational contact - | | |
| 14 | Shale, dark, in 1 to 2 m beds, interbedded with thin light-gray fine sandstone. Some 1-m-thick coaly layers especially near top.................................... | 16 | 151 |

| A | | B | C |
|---|---|---|---|
| | Sample F213A 6 m Medium- to dark-gray shale with *Dicroidium*. -sharp contact - | | |
| 15 | Sandstone, light-gray (w/red brown), medium- to coarse-grained, cross-bedded. Discoidal shale fragments up to 15 cm across at 10 and 13 m | 13 | 165 |
| | Sample F214 1.2 m Ss. - gradational contact - | | |
| 16 | Shale, black, coaly - slumped contact - | 7 | 172 |
| 17 | Sandstone, light-gray to white (w/red brown) medium-grained, cross-bedded. Finer in upper 2 m - gradational contact - | 6 | 178 |
| 18 | Shale, dark-gray to black. A few coaly layers | 8 | 186 |
| 19 | SNOW - slumped contact - | 1.5 | 187 |
| 20 | Sandstone, white to light-gray (w/red brown) medium-grained, cross-bedded. Concentrations of discoidal shale fragments up to 10 cm across occur at 0.6 and 1.5 m, associated with coal streaks | 4 | 191 |
| | Sample F215 3 m Ss. - gradational contact - | | |
| 21 | Shale, dark-gray | 8 | 199 |
| 22 | Sandstone, light-gray (w/red brown, fine- to medium-grained | 0.6 | 200 |
| 23 | Shale, dark-gray. One or two coaly and sandy beds about 60 cm thick - slumped contact - | 16 | 216 |
| 24 | Sandstone, light-gray (w/red brown), medium-grained, cross-bedded - gradational contact - | 3 | 219 |
| 25 | Shale, dark-gray - erosion surface - | 2.4 | 222 |

| A | | B | C |
|---|---|---|---|
| 26 | Sandstone, light-gray (w/red brown), fine-grained. Shale fragments in lower 2 m. Shaly stringers about 1 m thick appear in upper 1.2 m........................... | 9 | 231 |
| | Sample F216 base Erosion surface and ss. | | |
| | - gradational contact - | | |
| 27 | Shale, dark-gray...................................... | 6 | 237 |
| | - slumped contact - | | |
| 28 | Sandstone, light-gray, medium-grained, cross-bedded...... | 5 | 242 |
| | - gradational contact - | | |
| 29 | Shale, light-gray, sandy................................ | 13 | 255 |
| | - erosion surface - | | |
| 30 | Sandstone, light-gray, medium-grained. Discoidal and ovoid shale fragments up to 8 cm across abundant in lower 60 cm............................................ | 5 | 259 |
| | - gradational contact - | | |
| 31 | Shale, light-gray, sandy................................ | 5 | 264 |
| | - erosion surface - | | |
| 32 | Sandstone, light-gray, medium-grained. Discoidal and ovoid shale fragments up to 15 cm across in lower 30 cm and in lens at 1 m with a few coaly fragments.......... | 4 | 268 |
| | Sample F217 0.3 m Ss. | | |
| 33 | Shale, light-gray...................................... | 3 | 271 |
| | - erosion surface - | | |
| 34 | Sandstone, light-gray (w/red brown), medium- to coarse-grained, cross-bedded. Discoidal shale fragments up to 15 cm across and quartz pebbles up to 3 cm across. At 11 m there is a 10 cm layer of ovoid shale fragments up to 8 cm across and quartz pebbles up to 2 cm across. | 11 | 282 |
| | Sample F218 base Erosion surface and ss.<br>Sample F218A 11 m Pebbles | | |
| | - sharp contact - | | |
| 35 | Tuff, light-green-gray, fine-grained, massive to medium-bedded. Weathers into knobs several inches high. Pitted horizons at 16 and 21 m........................ | 24 | 306 |
| | Sample F219 11 m Tuff.<br>Sample F220 21 m Tuff. | | |
| | - erosion surface - | | |

| A | | B | C |
|---|---|---|---|
| 36 | Sandstone, light-gray (w/red brown), medium-grained. Basal 60 cm is a fine quartz pebble conglomerate with red garnet concentrates in the matrix, and shale fragments up to 40 cm long. Quartz grit with common garnet, and shale fragments up to 12 cm across, 30 cm thick at 15 m. For 3 m above and below this the sandstone has knobbles 1 cm across........................ | 16 | 322 |
| | Sample F221 15 m Ss.<br>- gradational contact - | | |
| 37 | Tuff, light-green-gray.................................. | 11 | 333 |
| | - erosion surface - | | |
| 38 | Sandstone, light-gray (w/red brown), medium-grained, massive, cross-bedded. Rounded, tabular shale fragments, mostly about 8 cm across but up to 30 cm across, are common close to lower contact, and at 1 m. Pebbles of quartz and indurated sandstone, as well as red garnet, are also common at these levels........................ | 9 | 342 |
| | Sample F222 0.6 m Ss.<br>Sample F223 0.6 m Conglomerate.<br>Sample F224 4 m Ss.<br>Sample F225 8 m Ss.<br>- sharp contact - | | |
| 39 | Sandstone (tuff?), coarsely mottled light-pink and gray, fine-grained, massive, very hard...................... | 1.8 | 344 |
| | - gradational contact - | | |
| 40 | Tuff, gray-green. Pitted in places. Contains flecks of secondary red analcime ................................ | 5 | 349 |
| | Sample F226 2.1 m Mudst.<br>- sharp contact - | | |
| 41 | Tuff, gray. Polygonal cracks? in lower surface. Very hard. 10 cm thick.................................. | | 349 |
| | - sharp contact - | | |
| 42 | Tuff, light-green-gray, massive, with white flecks. Weathers pitted. Quartz blebs 1 to 2 mm across. Red zeolite scattered throughout, but less abundant that in unit 40. Lens from 1.5 to 2.4 m has fine sandy pink laminae alternating with silty green laminae - disappears laterally in a few m. Further along the face a 0.6 m zone at 2 m was found to contain agate-filled vugs up to 2 cm long and about 0.6 cm across, lying | | |

| A | | B | C |
|---|---|---|---|
| | parallel to the lower surface of the unit. Vugs were also found at one or two higher levels............... | 5 | 354 |
| | Sample F228 base Tuff.<br>Sample F229 0.6 m Tuff.<br>Sample F230 1.8 m Part of concretion 5 cm across.<br>- gradational contact - | | |
| 43 | Tuff, in hard white and softer green layers from 10 to 30 cm thick (w/yellow, red, brown). Concretionary features 3 to 7 cm across are picked out by a black rim several mm thick. Red zeolite? occurs usually in the greenish layers.................................... | 12 | 367 |
| | Sample F231 11 m Concretion?.<br>- sharp contact - | | |
| 44 | Tuff, green, with irregular horizontal parting. Concretionary structures as above.......................... | 1.2 | 368 |
| | Sample F232 0.6 m Tuff.<br>- sharp contact - | | |
| 45 | Tuff, light-gray, massive. Concretionary structures 3 to 25 cm across common along base and scattered throughout........................................... | 5 | 373 |
| | Sample F233 base Tuff.<br>Sample F234 1.2 m Tuff.<br>- erosion surface - | | |
| 46 | Sandstone, light-gray, medium-grained, thin-bedded. A few purple fine sandstone beds 2 to 5 cm thick. Rounded spheroidal fine-grained fragments mostly about 1 or 2 cm across with some up to 15 cm across in the lower 0.6 m........................................ | 9 | 382 |
| | Sample F235 0.6 m Ss.<br>Sample F236 0.9 m Ss.<br>Sample F237 6 m Ss.<br>Sample F238 9 m Ss.<br>- gradational contact - | | |
| 47 | Tuff, light-gray (w/pink), massive, with abundant green angular lenticles. Weathers blocky. Lower contact undulating with 1 m of relief. Red zeolite? sparsely distributed throughout. Upper 1.2 m green but otherwise the same........................................ | 3 | 385 |

| A | | B | C |
|---|---|---|---|
| | Sample F239 0.6 m Tuff.<br>Sample F240 3 m Tuff.<br>- erosion surface - | | |
| 48 | Sandstone, light-gray, medium-grained, massive. Lower 0.6 m has abundant discoidal fragments mostly 1 to 2 cm across........................................ | 3 | 388 |
| | Sample F241 1.2 m Ss.<br>- gradational contact - | | |
| 49 | Tuff, varicolored (green-gray-pink-orange). Discoidal fragments 1 to 2 cm across common throughout. Red zeolite? common in lower part of unit. Weathering has produced distinct but discontinuous 30 cm thick layers. Some horizons have a well-developed vertical cleavage. Most of unit has a rude flaggy parting...... | 12 | 400 |
| 50 | SNOW, SCREE.............................................. | 9 | 409 |
| 51 | Tuff, light-gray, blocky. Massive light-gray (w/red brown), tuffaceous, cross-bedded, fine sandstone appears to occupy channel 0 to 2.4 m deep. Fragments up to 2.4 m deep. Fragments up to 35 cm across but mostly 1 to 2 cm across are common in lower 1 m of channel......... | 5 | 414 |
| | Sample F243 1.5 m Tuffaceous ss.<br>Sample F244 1.8 m Light-gray tuff.<br>Sample F245 5 m Light-gray tuff.<br>- sharp contact - | | |
| 52 | Tuff, white, with flecks of red zeolite?. 15 cm thick...<br>- gradational contact - | | 414 |
| 53 | Tuff, green..............................................<br>- gradational contact - | 0.3 | 414 |
| 54 | Tuff, white to pink, with well-developed columnar jointing............................................. | 3 | 417 |

NOTE: Unit 55 was described from a scree-covered slope on the southwest face of Mt. Falla. Bedrock was examined by digging every 2 m in the lower 30 m and every 4 m in the upper part of the unit. The thickness of unit 55 was determined by altimeter on the north face of Falla, where the contacts are better exposed.

| A | | B | C |
|---|---|---|---|
| 55 | Tuff, green-gray (brown gray in lower 15 m), massive to shaly. A few specks of red zeolite? in lower 24 m. Amygdaloidal from about 24 to 30 m. Black-coated accretionary lapilli up to 1 cm across are common from 40 m to the top of the unit. The upper 6 m on the north face of Falla is similar but appears sandier.. | 105 | 522 |

Sample F246 6 m Tuff.
Sample F247 22 m Tuff.
Sample F248 24 m Tuff, amygdaloidal.
Sample F249 40 m Tuff, with accretionary lapilli
Sample F249A 74 m Tuff with lapilli.
Sample F250 74 m Tuff with lapilli.
Sample F251 103 m Tuff, sandy, with lapilli.

| | | | |
|---|---|---|---|
| 56 | SNOW.................................................... | 6 | 528 |
| 57 | Sandstone (tuffaceous?), gray-brown, fine-grained......... | 0.6 | 529 |

Sample F252 0.3 m Ss.

- gradational contact -

| | | | |
|---|---|---|---|
| 58 | Fine conglomerate and sandstone in alternating beds 2 to 5 cm thick.............................................. | <u>0.6</u> | <u>530</u> |

- gradational contact -

Thickness of Falla Formation.............................. 530 m

<u>Prebble Formation</u>

- gradational contact -

1 Conglomerate, red-brown, poorly sorted, massive with cobbles up to 30 cm across. Horizons of coarse conglomerate about 10 m apart and 1 m thick weather to form vague terraces, and grade up and down into fine conglomerate with clasts up to 5 cm across. Most pebbles are light-gray or red-brown and very-fine-grained, and may be tuffaceous.

Sample F253 0.3 m Conglomerate.
Sample F254 9 m Part of doleritic pebble 25 cm across.
Sample F255 12 m Conglomerate.
Sample F256 29 Conglomerate.
Sample F257 44 m Conglomerate.

| | | | |
|---|---|---|---|
| 2 | SNOW.................................................... | <u>9</u> | <u>53</u> |

Thickness of Prebble Formation........................... 53 m

| A | | B | C |
|---|---|---|---|

Section KO. Base just above snow basin 1.8 km north of the rock summit of Mt. Kirkpatrick, on the north face.
Elevation at base of section about 3400 m (map est.).
Position 84° 18.7' S; 166° 16' E.

<u>Fremouw Formation</u>

SNOW.

DIABASE SILL, locally discordant, about 450 m thick. Sandstone of the Fremouw Formation crops out at base of sill (top of K1).

| | | B | C |
|---|---|---|---|
| 1 | Mudstone, light-gray (w/light green gray), sandy, massive. A few white flecks above 4 m.................. | 9 | 9 |
| | Sill 30 cm thick at 4 m.<br>Sample KOO1 0.6 m Mudst.<br>Sample KOO2 5 m Ss from 0.6 m lens. | | |
| 2 | Mudstone, light-gray (w/light green gray or light pink gray), sandy, massive. Rootholes at 4 m. Lens of fine sandstone 30 cm thick at 4 m................... | 5 | 14 |
| | Sample KOO3 4 m Fine ss. | | |

Thickness of Fremouw Formation (including K1) 90 + m
- contact snow-covered -

<u>Falla Formation</u>

| | | B | C |
|---|---|---|---|
| 1 | Sandstone, very-light-gray (w/white or light pink gray), medium-grained, quartzose, cross-bedded, massive..... | 8 | 8 |
| | Sample KOO4 2.1 m Ss. | | |
| | DIABASE SILL, 8 m thick. | | |
| 2 | Mudstone, light-gray (w/light green gray), sandy........ | 9 | 17 |
| | - erosion surface - | | |
| 3 | Sandstone, light-gray (w/white, yellow, red brown), medium- to coarse-grained, cross-bedded, massive. A few quartz pebbles up to 2 cm across.................. | 4 | 21 |

| A | | B | C |
|---|---|---|---|
| | Sample K005 1.5 m Ss.<br>-gradational contact - | | |
| 4 | Sandstone, light- to medium-gray (w/light green gray), medium-grained, cross-bedded, massive, with quartzose gritty layers........................................ | 7 | 28 |
| | Sample K006 2.4 m Ss.<br>- erosion surface - | | |
| 5 | Sandstone, light-gray (w/white, yellow, red brown and light green gray), medium-grained. Lower 30 cm has many rounded light-gray mudstone fragments mostly 3 cm with some up to 10 cm across..................... | 2.1 | 30 |
| | - sharp contact - | | |
| 6 | Mudstone, light- to medium-gray (w/light green gray or light pink gray), sandy. Fine sandstone lenses in places. Rootholes from 1.5 to 2.4 m. <u>Dicroidium</u> and stems at 1 m.......................................... | 4 | 34 |
| | Sample K007 0.9 m Mudstone with <u>Dicroidium</u>. | | |
| | Traversed about 400 m southwest across a scree slope to the upper contact of the same sill that underlies unit 1. The sill is clearly discordant and unit 8 (below) appears to be only a matter of meters higher in the section than unit 6. | | |
| 7 | SCREE.............................................. | 3 | 37 |
| 8 | Sandstone, light-gray, very-coarse-grained, quartzose. Occupies channel. Adjacent beds are of white fine sandstone.......................................... | 4 | 41 |
| | Sample K008 2.4 m Coarse ss.<br>- sharp contact - | | |
| 9 | Sandstone, light-gray (w/white or light pink gray), laminated. Gritty lenses from 1.8 to 3 m. 30 cm siltstone layers occasionally. A little cross-bedding Good parting lineation at 12 m....................... | 17 | 58 |
| | Sample K009 base Ss.<br>Sample K010 13 m Ss.<br>- gradational contact - | | |

| A | | B | C |
| --- | --- | --- | --- |
| 12 | Sandstone, light-gray (w/light green gray), fine- to medium-grained, massive.................................. | 4 | 98 |
| | - gradational contact - | | |
| 13 | Tuff, light-gray (w/white or light green gray), fine sandy................................................ | 12 | 109 |
| | Sample K014 6 m White tuff. | | |
| | - sharp contact - | | |
| 14 | Tuff, light-gray (w/white, red brown, yellow), thin-bedded............................................... | 1.5 | 111 |
| | - sharp contact - | | |
| 15 | Sandstone, light-gray (w/white, light yellow brown), fine-grained, coarsely laminated. Some mudstone beds less than 30 cm thick................................ | 4 | 115 |
| | - erosion surface - | | |
| 16 | Sandstone, light-gray (w/light green gray), medium-grained............................................... | 4 | 119 |
| | - gradational contact - | | |
| 17 | Tuff, light-gray (w/same or light green gray), fine sandy, massive. Irregular white flacks, and specks of red zeolite?. Channel from 5 to 6 m contains fine- to medium-grained sandstone........................... Dike of pebbly sandstone (like that in unit 13). 12 cm wide with sharp contacts, at 10 m. | 21 | 140 |
| | Sample K015 5 m Fine ss. | | |
| | Sample K016 6 m Tuff. | | |
| | - gradational contact - | | |
| 18 | Tuff, very-light-gray (w/white, pink, light brown), well-bedded, forms bluffs................................ | 7 | 147 |
| | Sample K017 5 m Mudst. | | |
| | - gradational contact - | | |
| 19 | Tuff, like unit 18, but contains scattered amygdales about 0.3 cm across, particularly from 11 to 12 m. Red zeolite? particularly common at this level also. A few black-rimmed spheroidal concretionary structures about 5 to 10 cm across............................ | 22 | 169 |
| | Sample K018 12 m Ss. | | |
| | - erosion surface - | | |

| A | | B | C |
|---|---|---|---|
| 20 | Sandstone, light-gray (w/red brown), medium-grained. Lower 60 cm has mudstone fragments mostly 3 cm across but up to 50 cm. Log 2 m long and 15 cm across........................................ | 5 | 174 |
| | Sample K019 2.4 m Ss. | | |
| | - sharp contact - | | |
| 21 | Mudstone (tuff?), very-light-gray (w/light gray and pink gray), vaguely laminated or massive, fine sandy. | 2.4 | 176 |
| | - sharp contact - | | |
| 22 | Sandstone, light-gray (w/light green gray), medium-grained, thin-bedded to massive...................... | 5 | 181 |
| | - sharp contact - | | |
| 23 | Tuff, very-light-gray (w/same or pink gray). Lower surface undulatory with 60 cm of relief. Lower 60 cm is columnar-jointed................................ | 21 | 202 |
| | Sample K020 base Tuff. | | |
| | Sample K021 0.6 m Tuff. | | |
| | Sample K022 4 m Tuff. | | |
| | Sample K023 20 m Tuff. | | |
| | Lenticles about 1 cm across in lower 30 cm. | | |
| | Fine-grained green fragments about 1 cm across in upper 9 m. | | |
| | - sharp contact - | | |
| 24 | Tuff, very-light-gray (w/same or light pink gray). Lower 60 cm columnar-jointed but grades laterally into massive and vaguely thin-bedded material....... | 32 | 234 |
| | Sample K024 32 m Tuff | | |
| | SCREE.......................................... | 3 | 237 |
| | Sandstone, light-gray (w/light green gray). Sample K026 7m Ss. | | |
| | SCREE. Moved about 800 m northeast onto the middle outcrop of the northwest face. | | |
| 25 | Sandstone, light-green-gray (w/same - red-brown in lower 30 cm), medium-grained, cross-bedded, massive......... | | 242 |
| | Sample K025 base Ss. | | |
| | - gradational contact - | | |

| A | | B | C |
|---|---|---|---|
| 26 | Sandstone, light-gray (w/very light gray or pink gray), fine-grained, massive.................................. | 2.4 | 245 |
| | - erosion surface - | | |
| 28 | Sandstone, light-gray (w/same or light green gray), medium- to coarse-grained, massive, cross-bedded. Conglomerate from 0 to 60 cm thick at base, with pebbles mostly about 2 cm across of many lithologies. Local gritty and pebbly lenses throughout............ | 12 | 258 |
| | - gradational contact - | | |
| 29 | Sandstone, light-gray (w/light green gray), fine-grained, massive.................................... | 0.9 | 259 |
| | - gradational contact - | | |
| 30 | Mudstone, light-gray (w/light green gray).............. | 8 | 267 |
| 31 | SCREE................................................ | 2.1 | 269 |
| 32 | Sandstone, light-gray (w/light green gray), medium-grained, poorly sorted, with a few small pebbles..... | 6 | 275 |
| | Sample K029 0.9 m Ss. | | |
| 33 | SCREE................................................ | 7 | 282 |
| | Thickness of Falla Formation.......................... | 282 m | |

Prebble Formation (Type Section)

| A | | B | C |
|---|---|---|---|
| 1 | Conglomerate, red-brown, massive, very poorly sorted. Clasts mostly 0.5 to 1 cm with some up to 7.5 cm across. Bed 3 cm thick of fine green sandstone at 5 m. Bed from 12 to 13 m with sharp upper contact and a few accretionary lapilli about 1 cm across...... | 20 | 20 |
| | Sample K030 1.5 m Conglomerate.<br>Sample K031 13 m Fine ss with lapilli. | | |
| | - sharp contact - | | |
| 2 | Sandstone, light-gray (w/green gray), fine-grained.... | 0.6 | 21 |
| | - slumped contact | | |
| 3 | Sandstone, red and green-gray, conglomeratic, poorly sorted. Lower 21 m is medium-bedded. Unit becomes massive and similar to unit 1 above 21 m, but has massive lenses up to about 3 m thick of much coarser material with boulders up to 65 cm across. Most are of green-gray mudstone (tuff?) and gray sandstone. | | |

| A | | B | C |
|---|---|---|---|
| | Above 34 m the unit becomes stratified and contains many thin sandy beds, but conglomeratic beds with pebbles up to 12 cm across for about 80 percent of the sequence. Above 55 m the unit is massive and coarser, similar to the lenses described above....... | 66 | 86 |
| | Sample K032 6 m Ss.<br>Sample K033 30 m Part of ss boulder.<br>- sharp discordant contact - | | |
| 4 | Tuff, light- to medium-gray (w/green gray), sandy, massive. Accretionary lapilli appear about 2.1 m.'.. | 32 | 118 |
| | Sample K034 2.4 m Tuff with accretionary lapilli..<br>Sample K035 23 m Same. | | |
| 5 | SCREE.................................................. | 38 | 156 |
| 6 | Agglomerate, dark-brown, very poorly sorted with fragments mostly 5 to 8 cm with some up to 40 cm across..<br>- gradational contact - | 4 | 160 |
| 7 | Conglomerate, purple, poorly sorted, bedded in upper part.................................................. | 4 | 164 |
| 8 | Tuff, purple, thinly bedded, and tuffaceous sandstone.. | 2.4 | 166 |
| | Thickness of Prebble Formation........................ | 166 m | |
| | Basalt flow. | | |

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